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Induction Motors and Adjustable-Speed Drive Systems

7.1 ENERGY CONSERVATION

The potential energy conservation in any system can best be determined by examining each element of the system and its contribution to the losses and inefficiency of the system. Every device that does any work or causes a change in the state of a material has energy losses. Thus, typical losses include the following:

1. Electrical transmission losses from the metering point to the system. (This is where the electric power consumption is measured and the power bill determined.)
2. Conversion losses in any power conditioning equipment. (This includes variable-frequency inverters and the effect of the inverter output on the motor efficiency.)
3. Electric motor losses to convert electric power to mechanical power.

4. Mechanical losses in devices such as gears, belts, and clutches to change the output speed of the motor.
5. Losses in the driven unit, such as a pump or fan or any other device that performs work on material.
6. Transmission losses, such as friction losses to move material from one location to another.
7. Losses caused by throttling or other means to control material flow by absorbing or bypassing excess output.

Each element in a particular system has an efficiency that can be defined as

$$E = \frac{\text{output power}}{\text{input power}}$$

or

$$\text{Losses} = \text{input power} - \text{output power}$$

The overall efficiency of the system is the product of the efficiencies of all elements of the system; thus,

$$E_{\text{overall}} = E_1 \times E_2 \times E_3 \times E_4 \times E_5$$

Therefore, the proper selection of each element can contribute to electric energy conservation.

This can be illustrated by an example of a constant-speed pumping system. The pumping system is to move water from one location to another at 1000 gpm with a static head of 100 ft. The friction head is 30 ft with a 4-in.-diameter supply pipe. What is the energy saving using a 5-in.-diameter supply pipe and an energy-efficient motor? [Table 7.1](#) shows a summary of the calculations for the two systems. The net result is an annual saving of 28,520 kWh, or 19.7% of the input. Note that the savings were achieved by improved performance in several elements: lower motor losses due to improved efficiency and lower horsepower required, lower pump losses due to increased efficiency and lower horsepower required, and lower pipe friction

TABLE 7.1 Summary Calculations for Example of Pump Installation

	4-in. supply pipe	5-in. supply pipe
Static head, ft	100	100
Friction head, ft	30	10
Total head, ft	130	110
Output hydraulic hp	25.25	25.25
Input hydraulic hp	37.83	27.78
Hydraulic efficiency	0.769	0.909
Pump efficiency	0.77	0.79
Pump input, hp	42.64	35.16
Motor standard hp	50	40
Motor efficiency at operating load	0.90	0.92
Motor input, hp	47.38	38.22
Transmission efficiency	0.978	0.982
System efficiency	0.521	0.649
System input, hp	48.46	38.91
System input, kW	36.15	29.02
Energy saving, kW	—	7.13
Annual saving, kWh	—	28,520
Percent savings	—	19.7

losses with improved hydraulic efficiency. The overall system efficiencies are as follows:

$$\begin{aligned} \text{4-in. system efficiency} &= 0.769 \times 0.77 \times 0.90 \times 0.978 \\ &= 0.521 \end{aligned}$$

$$\begin{aligned} \text{5-in. system efficiency} &= 0.909 \times 0.79 \times 0.92 \times 0.982 \\ &= 0.649 \end{aligned}$$

The conclusion is that the complete system needs to be considered to obtain the most energy-efficient installation. One aspect not to be overlooked is that the losses in the system are dissipated as heat at each device, such as the motors, pumps, and compressors.

Therefore, if the devices are in a conditioned environment, the effect of the losses or change in the losses on the conditioning system must also be considered.

In many installations, additional energy savings can be achieved by combining the fixed-speed induction motor with some method of varying the output speed of the unit. This is particularly true in any application in which output is a fluid flow that must vary in response to some other variable. A similar opportunity exists if output pressure must be controlled with a varying flow or varying input pressure.

Many fluid processes (including air processes) involve pumping the fluid to a high pressure and controlling flow and pressure to the required levels by throttling or bypassing. These throttling and bypass methods of control are inherently inefficient.

Centrifugal pumps, fans, and blowers have characteristics in accordance with the laws of fan performance, which state the following:

Flow varies directly with speed.

Pressure varies as the square of the speed.

Power varies as the cube of the speed.

These types of applications lend themselves to conversion from throttled constant-speed systems to adjustable-speed systems and offer a large potential for energy savings.

7.2 ADJUSTABLE-SPEED SYSTEMS

Many types of adjustable-speed systems are available. Some of the more popular types of adjustable-speed drives are the following: multispeed motors, adjustable-speed pulley systems, mechanical adjustable-speed systems, eddy current adjustable-speed drives, fluid drives, DC adjustable-speed systems, AC variable-frequency systems, and wound-rotor motors.

The selection of the most effective system for a specific application depends on a number of factors:

Life-cycle cost

First cost

- Duty cycle and horsepower range
- Energy consumption
- Control features required
- Size
- Performance
- Reliability
- Maintenance

To assist in the selection of an adjustable-speed drive system, let us examine the characteristics of the more popular ones. The DC adjustable-speed systems have been specifically excluded from this section since their characteristics and application technology are well known to those who apply them.

7.2.1 Multispeed Motors

As discussed earlier, multispeed motors can be obtained with the following output characteristics:

- Constant horsepower
- Constant torque
- Variable torque

However, in conventional multispeed motors, only a limited variety of speed combinations is available. One-winding, two-speed motors are available with 2-to-1 speed combinations such as

- 1750 rpm/850 rpm
- 1150 rpm/575 rpm

Two-winding, two-speed motors are available with speed combinations other than 2 to 1. Typical speed combinations are

- 1750 rpm/1150 rpm
- 1750 rpm/850 rpm
- 1750 rpm/575 rpm
- 1150 rpm/850 rpm

Thus, there are more combinations of speed ratios available in the two-winding, two-speed motors.

In addition, two-winding, four-speed motors are also available. A typical speed combinations is 1750 rpm/1150 rpm/850 rpm/575 rpm.

Since the power requirements for many fans and centrifugal pumps are a cube of the speed, the variable-torque multispeed motor can be used for two-step speed control, i.e., a high-speed and a low-speed operation. With a one-winding, two-speed motor, the output of the fan or pump on low speed will be 50% of the output on high speed, and the horsepower required will be 12.5% of high speed. [Figure 1.7](#) shows a fan load curve superimposed on the speed-torque curves for a variable-torque multispeed motor. In the case of a two-winding, two-speed motor with a combination of 1750 rpm/1150 rpm, the output of the fan or pump on low speed will be 67% of the output on high speed, and the horsepower required will be 30% of high speed. This is illustrated by [Fig. 1.8](#), which shows a fan load curve superimposed on the motor speed-torque curves. Given the speed limitations of this type of drive, it is an economical and reliable method to obtain incremental flow control.

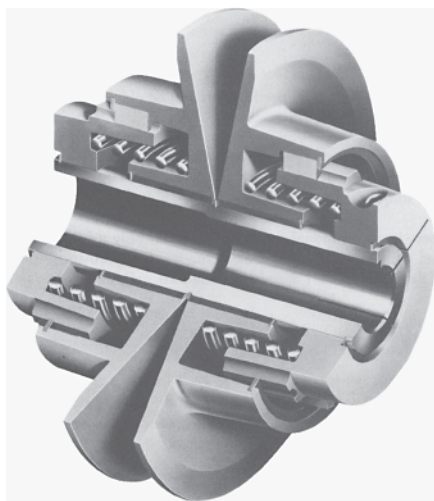


FIGURE 7.1 Variable-speed pulley. (Courtesy T. B. Wood's Sons Company, Chambersburg, PA.)

7.2.2 Adjustable-Speed Pulley Systems

An adjustable-speed pulley system consists of the electric motor mounted on a special base, an adjustable-speed sheave on the motor shaft, and a fixed-diameter sheave on the load shaft connected by a V belt. [Figure 7.1](#) shows the construction of one of the variable-speed sheaves, and [Fig. 7.2](#) shows the special base required for the drive motor.

[Figure 7.3](#) illustrates the cross-section construction of a double-side spring sheave, showing the maximum and minimum drive-belt locations, and [Fig. 7.4](#) shows the cross-section construction of a single-side spring sheave.

The double-side spring sheave is usually recommended for the integral-horsepower V-belt drives. The V belt in the spring-loaded sheave changes its diametric position as the base is adjusted, resulting in a change in the ratio of the effective pitch diameters of the driven and driving sheaves and a change in output speed. This type of drive has a limited capacity up to approximately 125 hp and

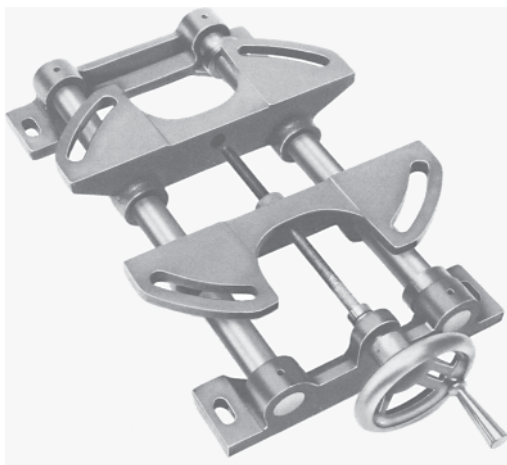


FIGURE 7.2 MBA motor base. (Courtesy T. B. Wood's Sons Company, Chambersburg, PA.)

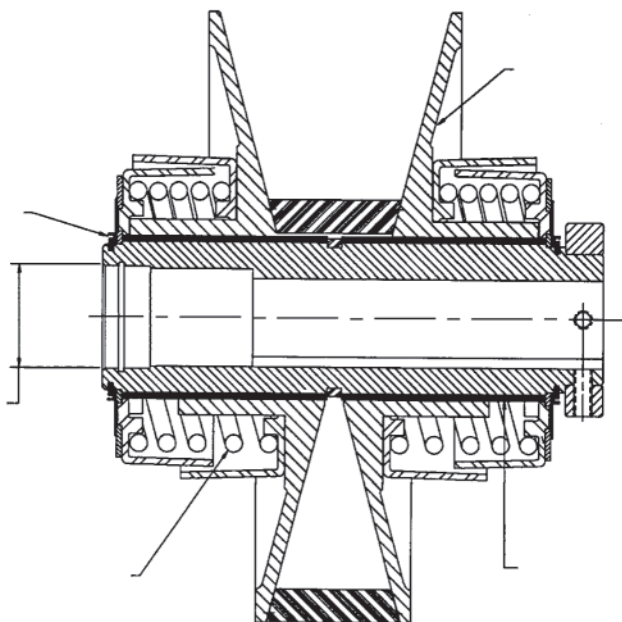


FIGURE 7.3 Cross section of double-side spring sheave. (Courtesy Lovejoy Inc., South Haven, MI.)

a limited speed range of approximately 2 or 3 to 1. In special cases, the speed range may be wider. The efficiency of these drives depends on the belt loading and minimum diameter of the sheaves. The belt efficiency as a function of load ranges from 92 to 99% and as a function of sheave diameter from 91 to 97%. When combined with a three-phase induction motor, the system efficiency ranges from 40 to 90%, depending on the type of load and speed reduction.

Figure 7.5 illustrates the system efficiency for an adjustable-speed pulley system with a 10-hp, 1750-rpm energy-efficient motor driving a constant-torque load over a 3-to-1 speed range.

Figure 7.6 illustrates the system efficiency for an adjustable-speed pulley system with a 10-hp, 1750-rpm energy-efficient motor driving

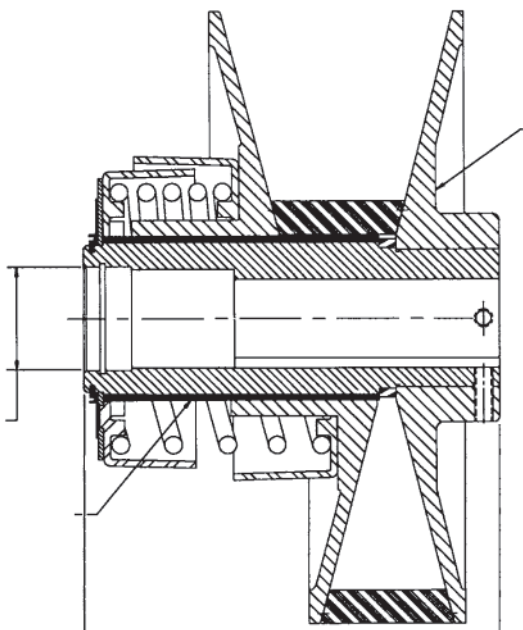


FIGURE 7.4 Cross section of single-side spring sheave. (Courtesy Lovejoy Inc., South Haven, MI.)

a variable-torque load over a 3-to-1 speed range. Its major disadvantage is that the speed must be changed manually and does not lend itself to automatic or remote control. However, for applications that require only occasional adjustment in output, this system may be adequate and still provide energy savings at the lower speed settings, for example, an air-handling system that requires output adjustment only for summer and winter operation. [Figure 7.7](#) shows a typical installation of this type of drive.

7.2.3 Mechanical Adjustable-Speed Systems

The broad group of mechanical adjustable-speed drives includes the more common stepless mechanical adjustable-speed drives that

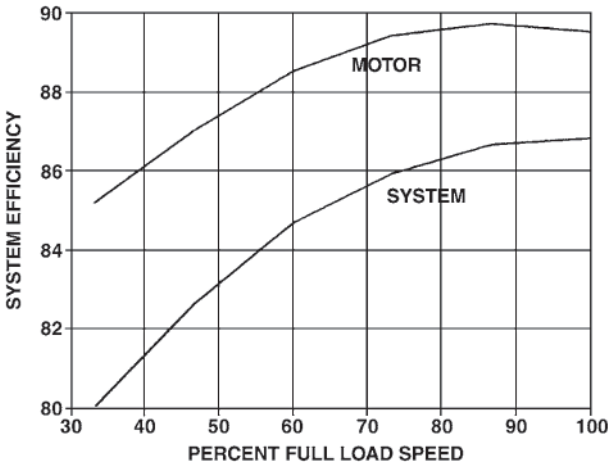


FIGURE 7.5 Adjustable-speed pulley system with a 10-hp energy-efficient motor driving a constant-torque load.

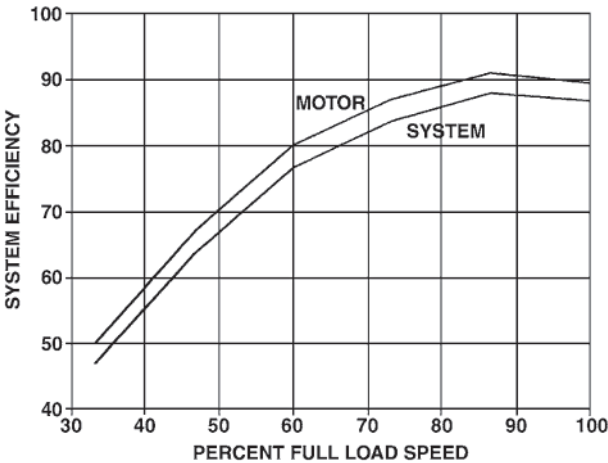


FIGURE 7.6 Adjustable-speed pulley system with a 10-hp energy-efficient motor driving a variable-torque load.

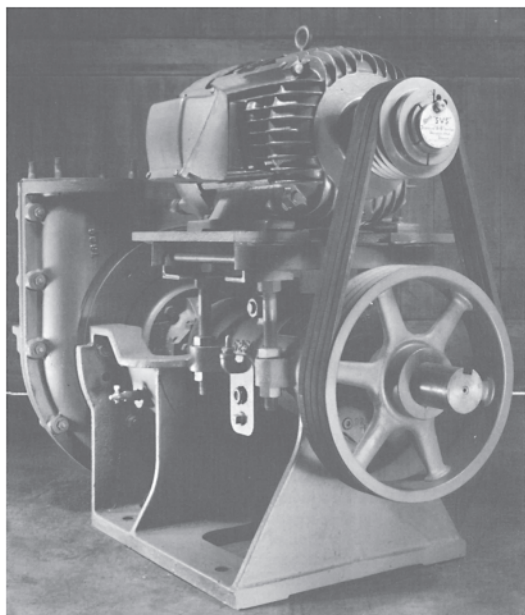


FIGURE 7.7 Installation of variable-speed sheave. (Courtesy T. B. Wood's Sons Company, Chambersburg, PA.)

provide an infinite number of speed ratios within a nominal speed range. These type of drives include packaged belt and chain drives, friction drives, and traction drives. These drive systems are usually driven by a constant-speed induction motor and convert this constant-speed input into a stepless variable-speed output.

[Figure 7.8](#) is a cross section of the assembly of the U.S. Electric Motors varidrive system, showing the electric motor, driver, driven sheaves, and speed-adjusting mechanism.

A typical group of packaged adjustable-speed belt-drive systems is shown in [Fig. 7.9](#). In the case of the belt-drive systems, the basis of rating is generally constant torque (variable horsepower) at speed ratios below 1 to 1 and constant horsepower (variable torque) at speed ratios above 1 to 1. [Figure 7.10](#) illustrates this basis of rating.

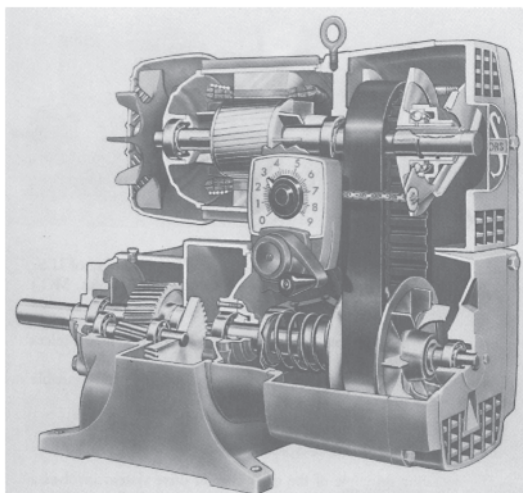


FIGURE 7.8 Cross section of U.S. Electrical Motors Varispeed System. (Courtesy U.S. Electrical Motors, Division of Emerson Electric Co., St. Louis, MO.)

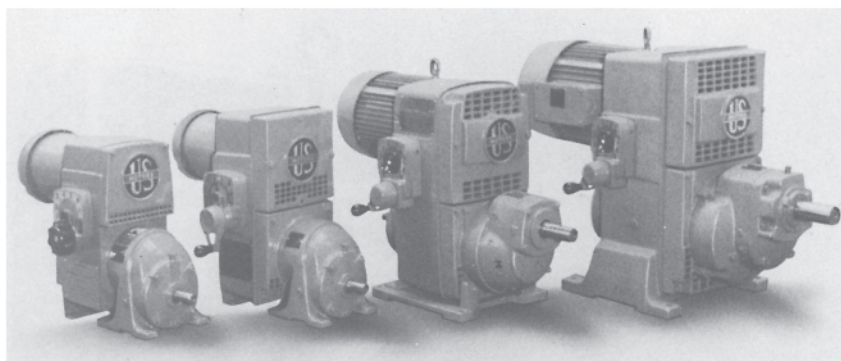


FIGURE 7.9 U.S. Electrical Motors varidrive units. (Courtesy U.S. Electrical Motors, division of Emerson Electric Co., St. Louis, MO.)

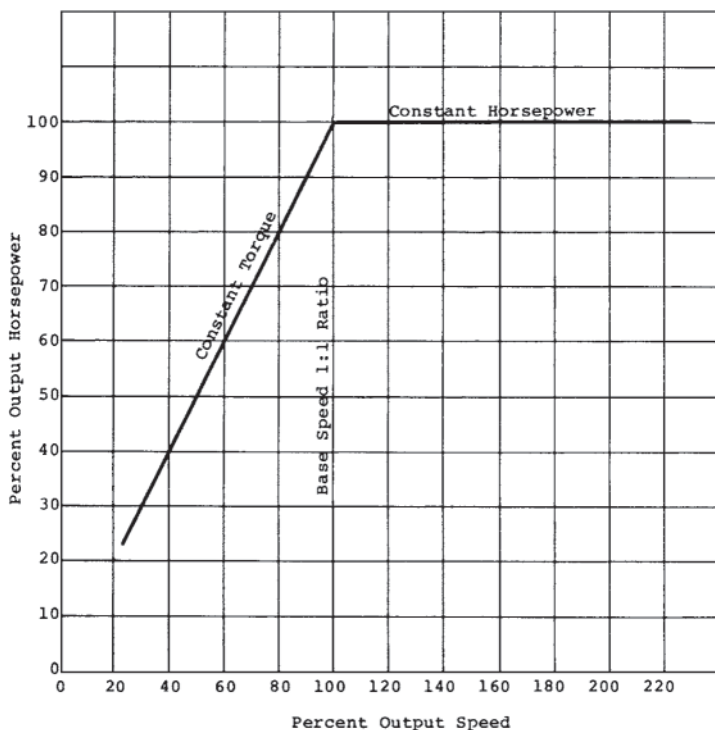


FIGURE 7.10 Horsepower output versus output speed of a mechanical adjustable-speed drive system. (Courtesy U.S. Electrical Motors, division of Emerson Electric Co., St. Louis, MO.)

The efficiency of these systems at various loads and speeds is shown in Figs. 7.11 and 7.12 for representative ratings of the varidrive line of packaged mechanical belt drives.

Most of these types of drives have limited horsepower and speed ranges. Therefore, the selection of the drive systems should be based on the duty cycle of the load and the characteristics of the drive under consideration, including speed range, horsepower, torque characteristics, and efficiency over the duty cycle. When properly

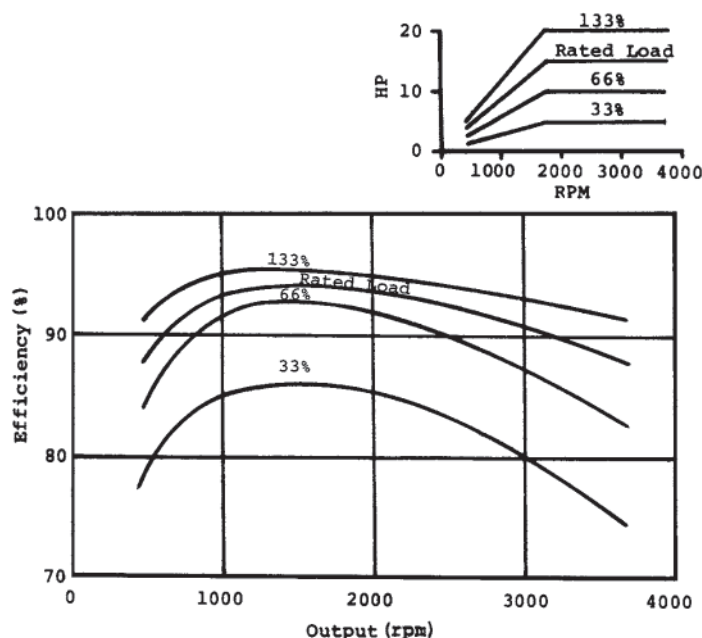


FIGURE 7.11 Varidrive performance curves, typical data for a 15-hp, four-pole motor. (Courtesy U.S. Electrical Motors, division of Emerson Electric Co., St. Louis, MO.)

applied, many of these drives have good efficiencies over their operating range. It is recommended that several types of systems be compared to determine the most suitable and effective life-cycle cost system. The requirements and type of remote control must also be a factor in the selection of the drive system.

Figures 7.13–7.15 illustrate the types of process controls available on packaged belt drives.

7.2.4 Eddy Current Adjustable-Speed Drives

The operating principle of the eddy current drive system involves a constant-speed AC induction motor that is magnetically coupled to

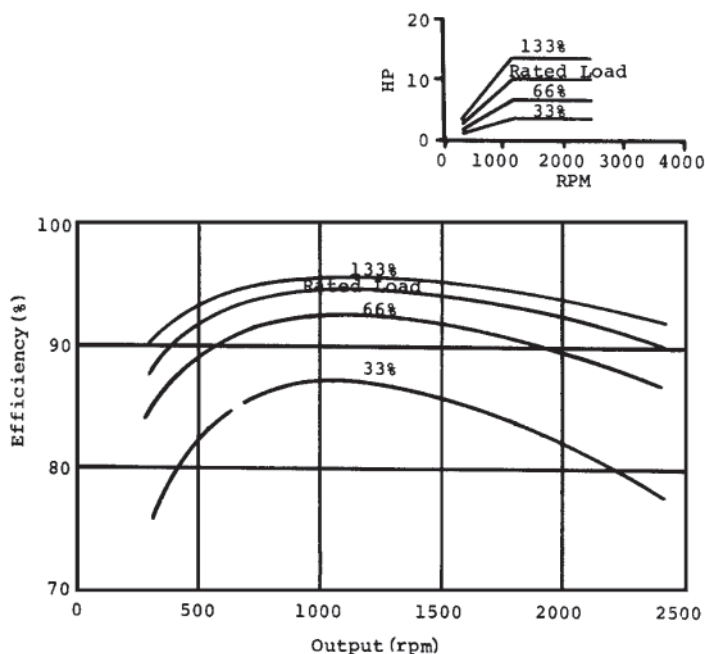


FIGURE 7.12 Varidrive performance curves, typical data for a 10-hp, six-pole motor. (Courtesy U.S. Electrical Motors, division of Emerson Electric Co., St. Louis, MO.)

an output shaft through an integral variable-speed eddy current coupling. The eddy current coupling consists of a constant-speed drum that is directly connected to the drive motor rotor and an inductor that is directly connected to the output shaft. As the drum rotates, eddy currents are induced and magnetic attraction occurs between the drum and the inductor, thus transmitting torque from the constant-speed drum to the output inductor. An excitation winding, which is usually stationary, is located in the magnetic circuit and is excited by a DC current to provide the magnetic field in the constant-speed drum and variable-speed inductor. The application of the field current creates a magnetic flux across the air

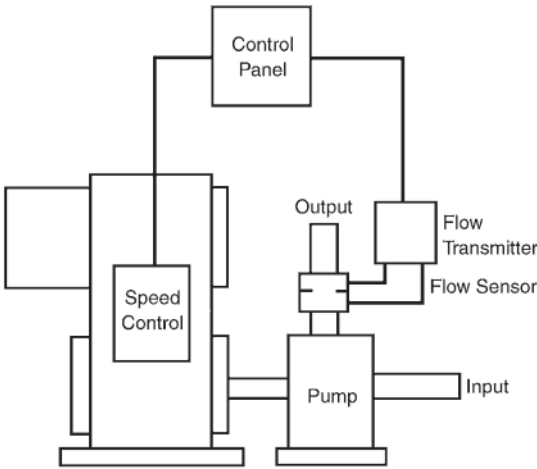


FIGURE 7.13 Output flow control of a mechanical adjustable-speed system.

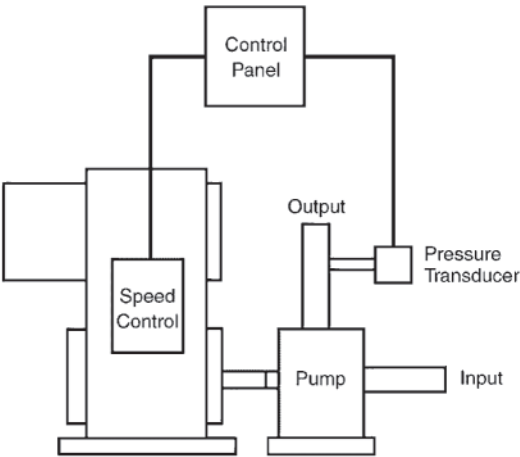


FIGURE 7.14 Line pressure control of a mechanical adjustable-speed system.

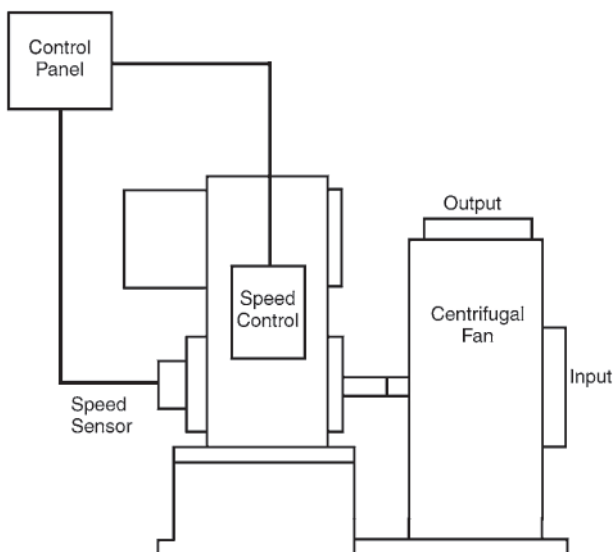


FIGURE 7.15 Speed control of a mechanical adjustable-speed system.

gap between the two members of the clutch, which induces eddy currents in the input drum. The net result is a torque available at the output shaft. The variation in the field current varies the degree of magnetic coupling between the motor-driven constant-speed drum and the variable-speed inductor connected to the output drive shaft. By adjustments in the field current, the output speed can be adjusted to match the output load requirements (speed and torque). Figure 7.16 shows the cross-section assembly of a self-contained eddy current drive system. Figure 7.17 is a general view of such a system. The power flow for this type of adjustable-speed drive is shown in Fig. 7.18.

The degree of coupling or slip between the two members is determined by the load and level of excitation. The slipping action (i.e., difference in speed) is the source of the major power loss and

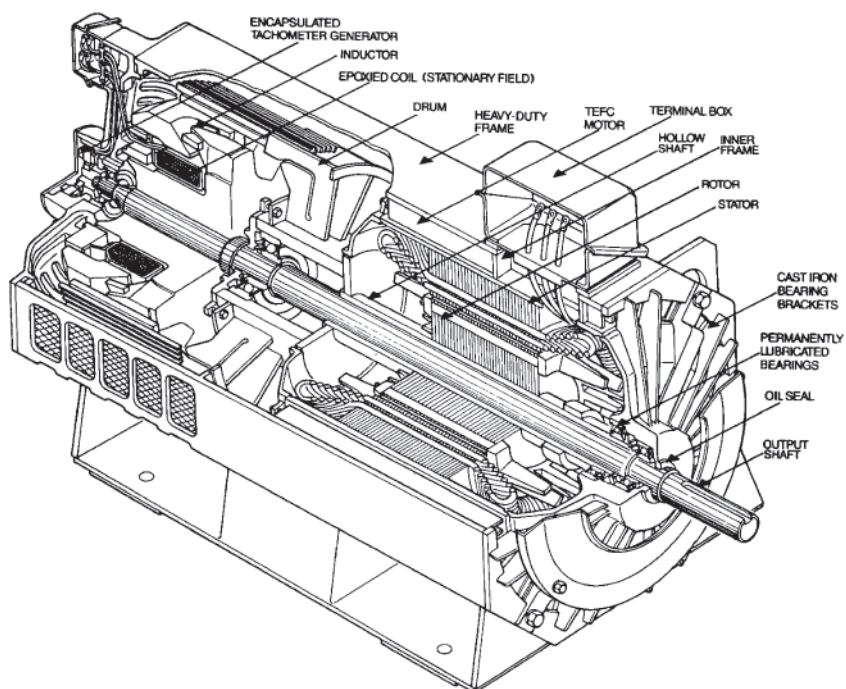


FIGURE 7.16 Cross section of self-contained eddy current adjustable-speed drive system. (Courtesy Magnetek, New Berlin, WI.)

inefficiency of the eddy current coupling. This slip loss is the product of the slip rpm, which is the difference in speed between the input and output members and the transmitted torque. This relationship may be expressed as follows:

$$\text{Load (output) hp} = \frac{\text{rpm}_2 T_L}{5252}$$

$$\text{Motor (input) hp} = \frac{\text{rpm}_1 T_L}{5252}$$

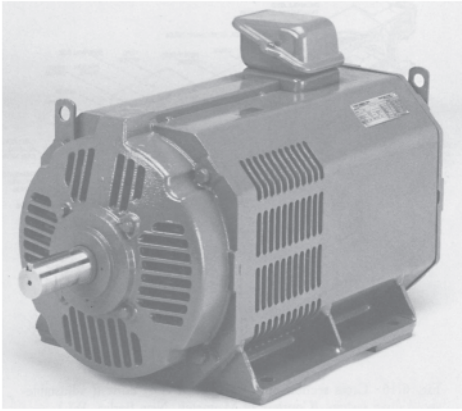


FIGURE 7.17 Self-contained eddy current adjustable-speed drive system. (Courtesy Magnetek, New Berlin, WI.)

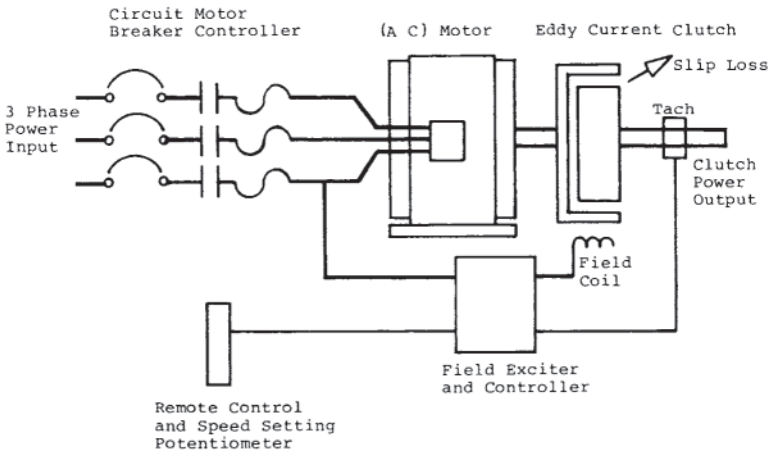


FIGURE 7.18 Power flow for eddy current drive system.

$$\begin{aligned}\text{Slip loss} &= \text{motor hp} - \text{load hp} \\ &= \frac{T_L(\text{rpm}_1 - \text{rpm}_2)}{5252}\end{aligned}$$

where

rpm_1 = coupling input speed (motor)

rpm_2 = coupling output speed (load)

T_L = load torque, ft-lb

The efficiency of an eddy current coupling can never be greater than the numerical percentage of the output speed. However, in addition to the slip losses, the friction and windage losses and excitation losses of the coupling must also be included in the efficiency determination. The friction and windage loss is about 1% of the rated input horsepower and can be considered constant over the speed range. The excitation loss is less than 0.5% of the input horsepower and decreases with reduction in speed. The maximum torque developed by the drive is limited to the maximum torque (breakdown torque) of the induction drive motor or the magnetic coupling of the eddy current clutch. With proper matching of the drive components, the full capacity of the drive motor can be utilized. [Figure 7.19](#) illustrates the overload capacity of an eddy current drive system with an induction motor driver.

Since the eddy current coupling has no inherent speed regulation, it is necessary that the coupling include a tachometer generator that rotates at the coupling output speed. The tachometer-generator output signal is fed into a speed-control loop in the excitation system to provide close output speed regulation. The speed regulation is usually $\pm 1\%$ but with closed-loop control may be as close as $\pm 0.1\%$. In addition to speed, the eddy current-control system can be used with any type of actuating device or transducer that can provide a mechanical translation or an electrical signal. Actuating devices include liquid-level control, pressure control, temperature control, and flow control. The performance of the eddy current adjustable-speed drive system driving a constant-torque load is illustrated in [Fig. 7.20](#). The speed range for continuous operation is usually 16:1 but can be wider, depending

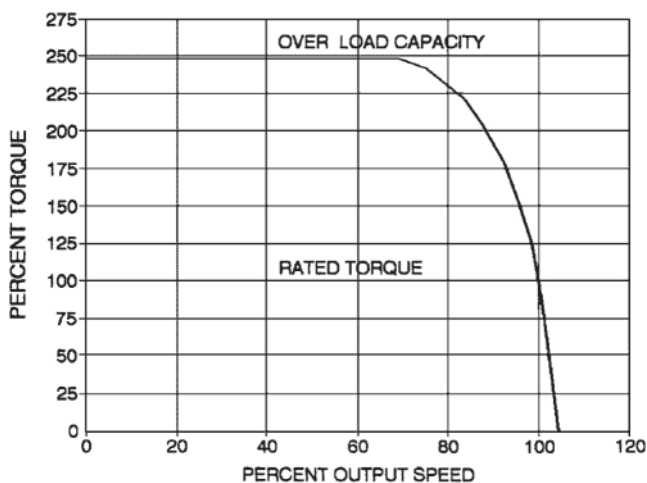


FIGURE 7.19 Eddy current adjustable-speed drive overload capacity.

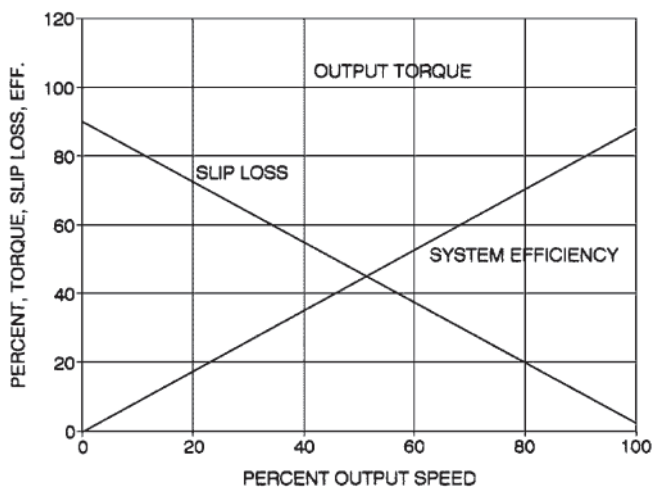


FIGURE 7.20 Eddy current adjustable-speed drive applied to a constant-torque load.

on the thermal dissipation capacity of the eddy current clutch. The performance of the eddy current adjustable-speed drive system driving a variable-torque load is illustrated in Fig. 7.21. The speed range shown in Fig. 7.21 is down to only 45% speed, which is within the range of most variable-speed applications; however, the eddy current drive can supply these types of loads to much lower speeds if necessary.

The advantages of this type of adjustable-speed drive are

Eddy current simplicity and high reliability

Stepless variable-speed control

Good speed regulation

High starting torque

High overload capacity

Controlled acceleration

Handle high-impact loads.

Figure 7.22 illustrates the application of an eddy current adjustable-speed drive to an extruder. Figure 7.23 illustrates the application of the eddy current adjustable-speed drive to a process pump.

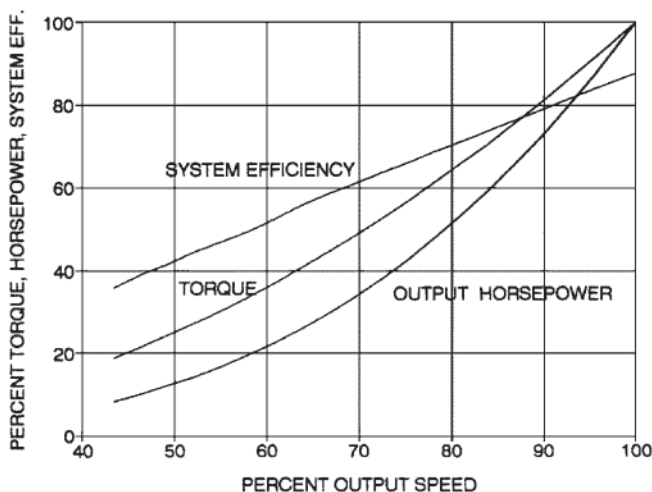


FIGURE 7.21 Eddy current adjustable-speed drive applied to a variable-torque load.

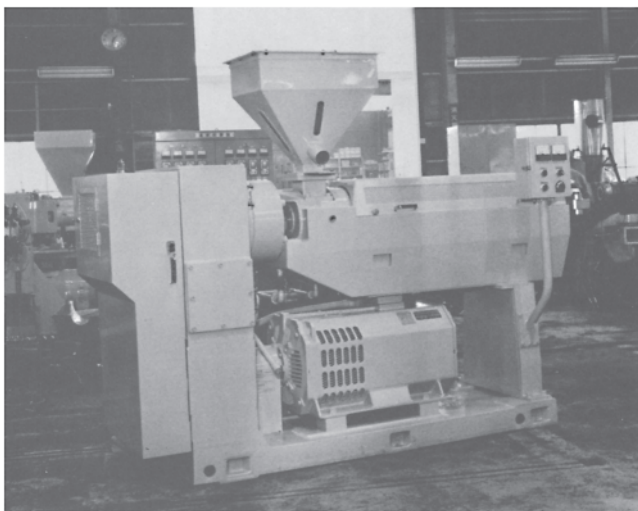


FIGURE 7.22 The application of an eddy current adjustable-speed drive system to an extruder. (Courtesy Magnetek, New Berlin, WI.)

7.2.5 Fluid Drives

Fluid drives can be described as any device utilizing a fluid to transmit power. The fluid generally used is a natural or synthetic oil. Fluid drives can be grouped into four categories: (1) hydrokinetic, (2) hydrodynamic, (3) hydroviscous, and (4) hydrostatic. The hydrokinetic, hydrodynamic, and hydroviscous drives are all slip-type devices.

The hydrokinetic fluid drive, commonly referred to as a fluid coupling, consists of a vaned impeller connected to the driver and a vaned runner connected to the load. The oil is accelerated in the impeller and then decelerated as it strikes the blades of the runner. Thus, there is no mechanical connection between the input and output shafts. Varying the amount of oil in the working circuit changes the speed. This provides infinite variable speed over the operating range of the drive. [Figure 7.24](#) is a representation of such a drive.

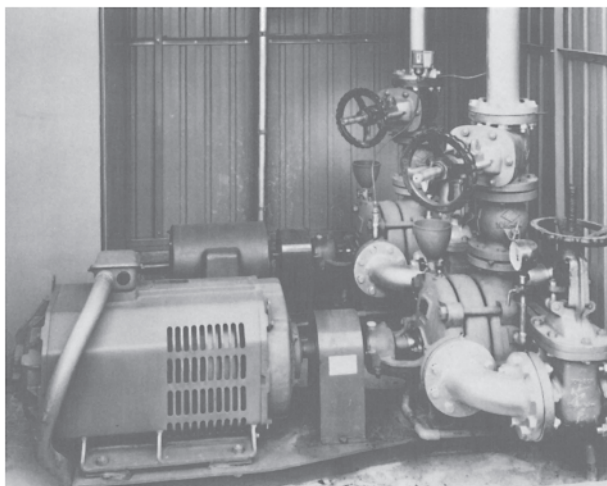


FIGURE 7.23 The application of an eddy current adjustable-speed drive system to a process pump. (Courtesy Magnetek, New Berlin, WI.)

The circulating pump, driven from the input shaft, pumps oil from the reservoir into the housing through an external heat exchanger and then back to the working elements. The working oil, while it is in the rotating elements, is thrown outward, where it takes the form of a toroid in the impeller and runner. Varying the quantity of oil in this toroid varies the output speed. A movable scoop tube controls the amount of oil in the toroid. The position of the scoop tube can be controlled either manually or with automatic control devices. The scoop-tube adjustment gives a fast response and smooth stepless speed control over a wide speed range, i.e., 4 to 1 with a constant-torque load and 5 to 1 with a variable-torque load. In addition to providing speed control, the fluid drive limits torque and permits no-load starting on high-inertia loads.

These units range in size from 2 to 40,000 hp, as illustrated in [Fig. 7.25](#).

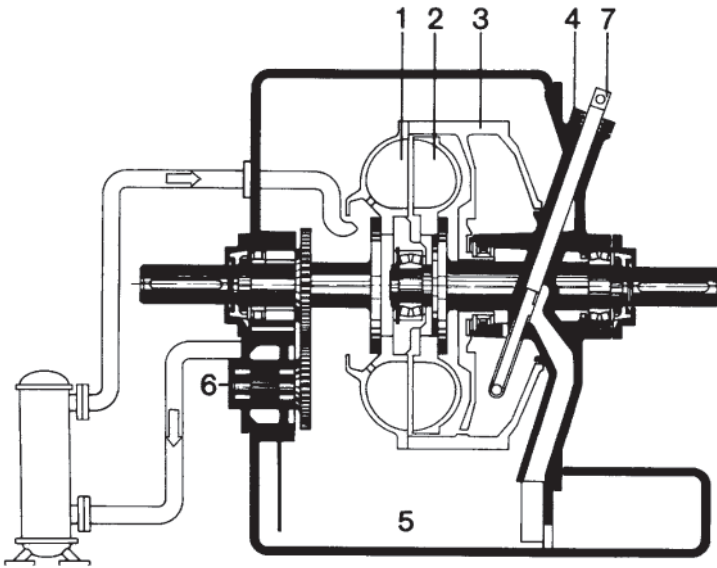


FIGURE 7.24 Diagram of a hydrokinetic drive: (1) primary wheel; (2) secondary wheel; (3) shell; (4) scoop tube housing; (5) oil sump; (6) oil pump; (7) scoop tube. (Courtesy Voith Transmissions, Inc., York, PA.)

Efficiency. The fluid drives have two types of losses:

Circulation losses. These losses include friction and wind-age losses, the power to accelerate the oil within the rotor, and the power to drive any oil pumps that are part of the system. These losses are relatively constant and are approximately 1.5% of the unit rating.

Slip losses. As in the case of eddy current couplings, the torque at the input shaft is equal to the torque required at the output shaft:

$$\text{Load (output) hp} = \frac{\text{rpm}_2 T_L}{5252}$$

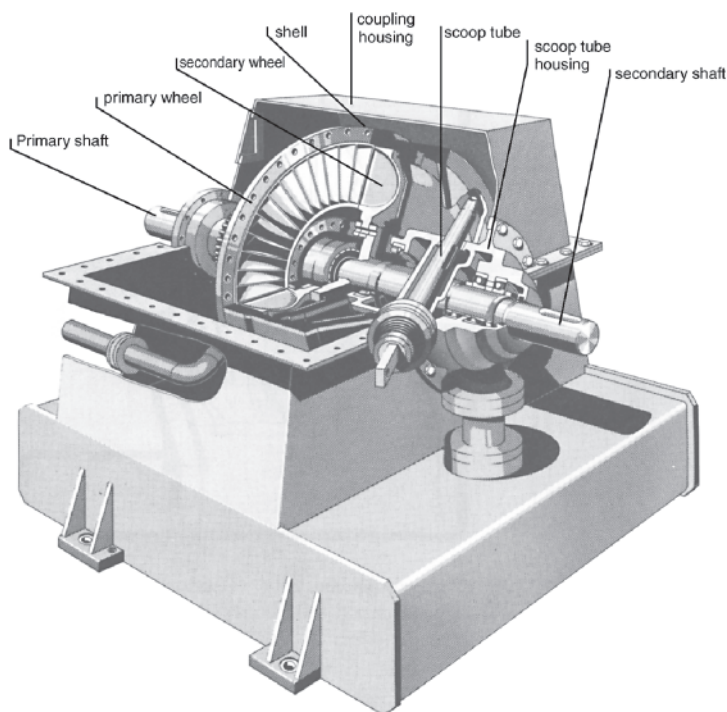


FIGURE 7.25 Voith hydrokinetic fluid drive. (Courtesy Voith Transmissions, Inc., York, PA.)

$$\text{Motor (input) hp} = \frac{\text{rpm}_1 T_L}{5252}$$

$$\text{Slip loss} = \text{motor hp} - \text{load hp}$$

$$= \frac{T_L(\text{rpm}_1 - \text{rpm}_2)}{5252}$$

where

$$\text{rpm}_1 = \text{coupling input speed (motor)}$$

$$\begin{aligned}\text{rpm}_2 &= \text{coupling output speed (load)} \\ T_L &= \text{load torque, ft-lb}\end{aligned}$$

The slip efficiency is then

$$\begin{aligned}\frac{\text{Input hp} - \text{slip loss}}{\text{Input hp}} \times 100 \\ = \frac{(T_L \text{rpm}_1 / 5252) - (T_L / 5252)(\text{rpm}_1 - \text{rpm}_2)}{T_L \text{rpm}_1 / 5252} \times 100 \\ = \frac{\text{rpm}_2}{\text{rpm}_1} \times 100\end{aligned}$$

$$\text{Total input hp} = \frac{\text{output hp}}{\text{slip eff}} + \text{circulation hp losses}$$

$$\text{Coupling efficiency} = \frac{\text{output hp}}{\text{input hp}} \times 100$$

The maximum speed of the fluid drive at full load is about 98% of the driving motor speed, and with circulation losses of 1.5% the maximum efficiency is 96.5% at a maximum speed.

Figure 7.26 illustrates the typical performance of a fluid coupling driving a variable-torque load such as a fan or pump, where the torque varies as the speed squared and the horsepower varies as the speed cubed. Figure 7.27 illustrates the performance of a fluid coupling driving a constant-torque load such as a conveyor or piston pump, where the horsepower varies as the speed. Figure 7.28 illustrates a complete-package adjustable-speed fluid drive consisting of the drive motor, fluid coupling, and necessary accessories. Figure 7.29 shows the installation of a variable-speed fluid-drive system driving mud pumps at a mining installation. Figure 7.30 shows the installation of variable-speed fluid-drive systems driving blowers.

More complex units are available at ratings generally above 1000 hp. The Voith MSVD multistage variable-speed drives are an example of these drives, which consist of

- Hydrodynamic variable-speed coupling
- Hydraulic-controlled lock-up clutch

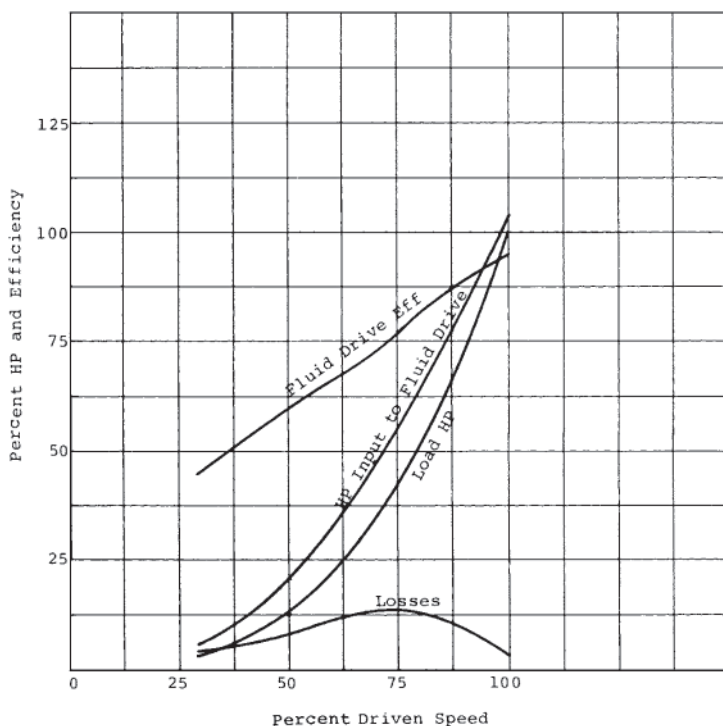


FIGURE 7.26 Fluid-coupling variable-speed drive characteristics when driving a load that varies as the speed cubed.

Hydrodynamic torque converter

Hydrodynamic brake

Planetary gear, fixed

Planetary gear, revolving

The operation of these units can be divided into two stages. In stage 1, the power is transmitted by the hydrodynamic variable-speed coupling directly through the planetary gear. The speed is controlled by changing the level of the oil in the hydrodynamic

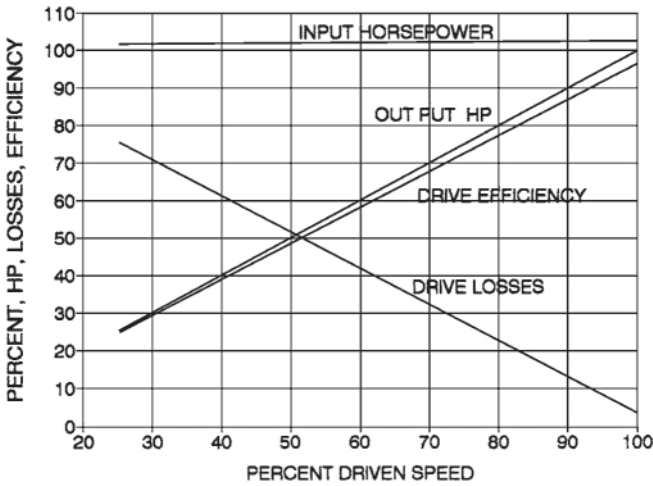


FIGURE 7.27 Fluid-coupling variable-speed drive characteristics when driving a constant-torque load.

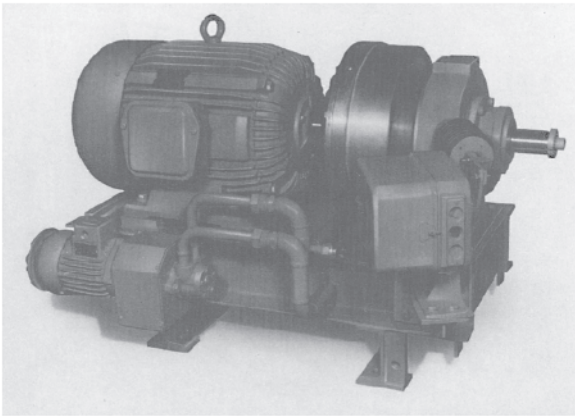


FIGURE 7.28 Packaged fluid drive consisting of the drive motor, fluid coupling, and necessary accessories. (Courtesy Voith Transmissions, Inc., York, PA.)

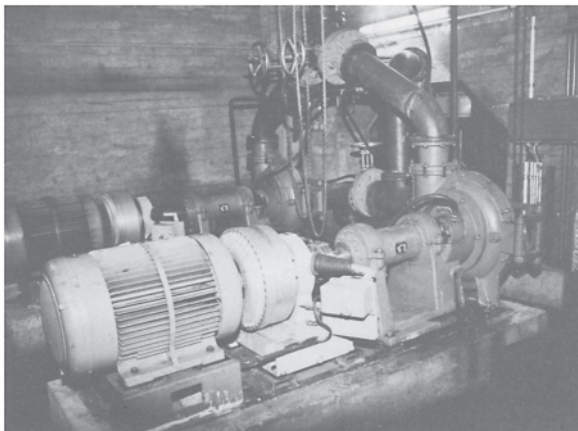


FIGURE 7.29 Variable-speed fluid drives driving mud pumps at mining installation. (Courtesy Voith Transmissions, Inc., York, PA.)

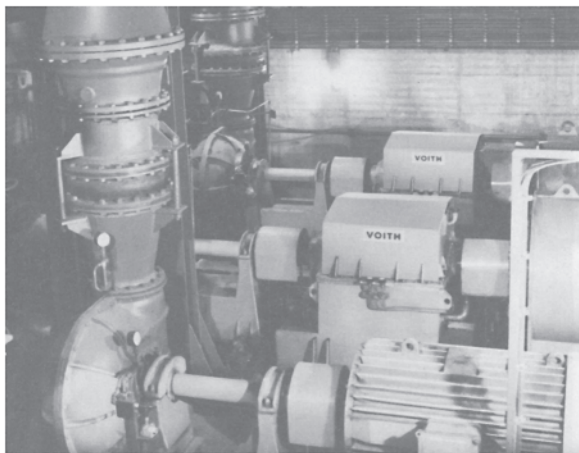


FIGURE 7.30 Variable-speed fluid drives driving blowers. (Courtesy Voith Transmissions, Inc., York, PA.)

coupling. The operating range is approximately 0–80% speed. The torque converter has no function in this stage. The hydrodynamic brake generates the countertorque for the planetary gear. In stage 2, the impeller and turbine wheel on the hydrodynamic coupling are locked together by the hydraulic-controlled clutch bridging the input and output elements so that the drive motor is now coupled mechanically to the driven load. The operating speed range in this stage is 80–100% and is controlled by the hydrodynamic torque converter.

Hydrostatic Drives. A hydrostatic variable-speed drive consists of a positive-displacement hydraulic pump driven by an induction motor, a positive-displacement hydraulic motor, and necessary hydraulic controls. The hydraulic pump and motor are usually separate units. This type of drive is also offered as a package consisting of the hydraulic pump, the piping, and the hydraulic motor mounted in a common housing.

When the hydraulic pump is driven by a constant-speed AC induction motor, the variable output is obtained by controlling the speed of the hydraulic motor. Commonly, the easiest system to design may be the most energy inefficient. Throttling any valve in the hydraulic system generates heat and consumes energy. The significance of this power loss is expressed as follows:

$$\text{Power loss (hp)} = \frac{\text{pressure drop (psi)} \times \text{flow (gpm)}}{1714 \times \text{pump efficiency}}$$

The most efficient hydraulic system is one that has no valves. However, such a system will also have very limited speed control. Many methods of control have been developed for hydraulic systems, and the method used depends on the types of pump and motor used and the characteristic of the load. Many of the systems are used on mobile equipment and machine tools, but they are not generally cost effective on industrial applications such as pumps and fans.

The Gibbs V/S drive shown in [Fig. 7.31](#) is a packaged hydrostatic drive consisting of a constant-speed electric-drive motor, a constant-speed

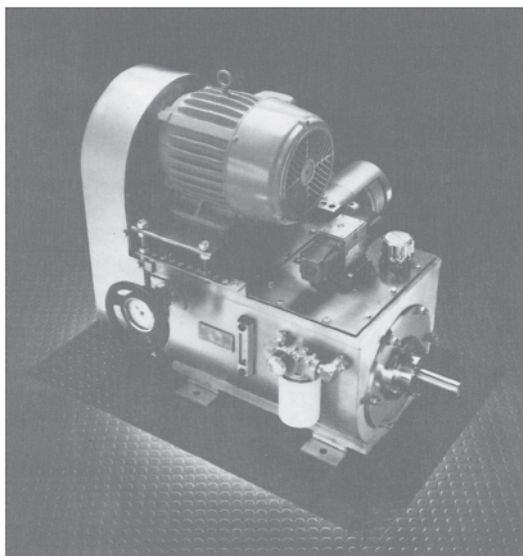


FIGURE 7.31 Gibbs V/S hydrostatic drive package. (Courtesy Gibbs Machine Co. Inc., Greensboro, NC.)

hydraulic pump, and a variable-speed hydraulic motor. The hydraulic pump is a variable-volume positive-displacement pump, and the hydraulic motor is a fixed-volume positive-displacement motor. In the Gibbs package unit, the hydraulic pump is about 87% efficient over its working range, and the hydraulic motor has an efficiency of 92% over the working range. [Figure 7.32](#) shows the hydraulic efficiency and the overall system efficiency for a 10-hp, 1800-rpm package unit operating over a 4:1 speed range, with a constant-torque load.

These types of adjustable-speed drives can operate from 0 to maximum speed at constant torque, with a recommended usable range of 27:1. The maximum output speed depends on the selection of the hydraulic motor in the package drive. These package drives are available up to 75 hp and can be provided with manual,

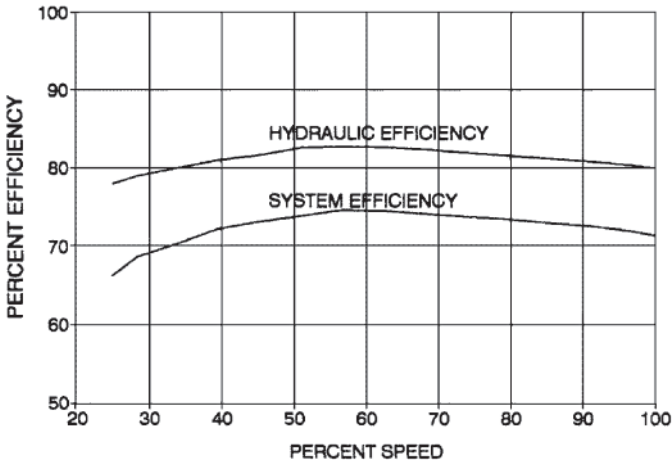


FIGURE 7.32 Efficiency of a hydrostatic package-drive unit driving a constant-torque load. (Courtesy Gibbs Machine Co., Greensboro, NC.)

electronic, pneumatic, or hydraulic controls. This type of drive is basically a constant-torque drive and is not normally used on variable-torque loads.

Hydroviscous Drives. Another class of adjustable-speed fluid drives are the hydroviscous drive units. The basic components of the hydroviscous drive are (1) the torque-transmitting clutch plates, pressure plate, and flywheel assembly; (2) the oil pump for cooling and controlling oil; (3) the variable-orifice controller and control piston with a torque-limiting valve. [Figure 7.33](#) is a cross section of one of these drives, manufactured by Great Lakes Hydraulic, Inc., showing the various components of the drive. [Figure 7.34](#) shows a complete assembly for a horizontal unit.

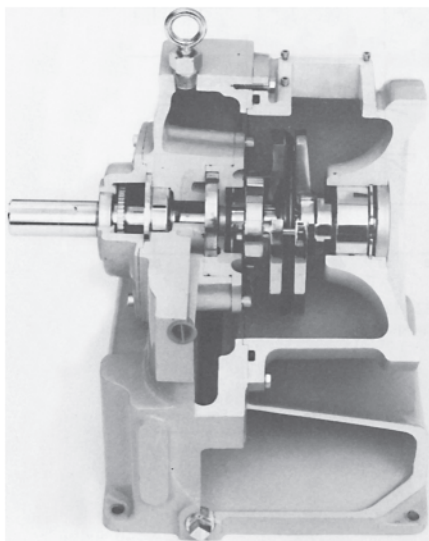


FIGURE 7.33 Cross section of a hydroviscous clutch assembly. (Courtesy Great Lakes Hydraulics, Inc., Grand Rapids, MI.)

There is a continuous flow of fluid between the constant-speed and adjustable-speed elements. The torque is transmitted through this film of fluid according to the oil shear principle. The amount of torque transmitted is proportional to the amount of piston pressure applied. As the piston pressure increases, the slip between the plates decreases. At the maximum rated piston pressure, the plates are locked in, and the output shaft is then running at input motor speed. The orifice controller determines the pressure supplied to the piston area. Minimum pressure is supplied to the piston when the orifice is completely open, bypassing fluid to the sump. The piston pressure is increased as the orifice is closed, and the slip between the clutch plates decreases. The orifice controller, which controls the piston pressure, can be manual, pneumatic, hydraulic, or electronic, as required. With automatic control, the

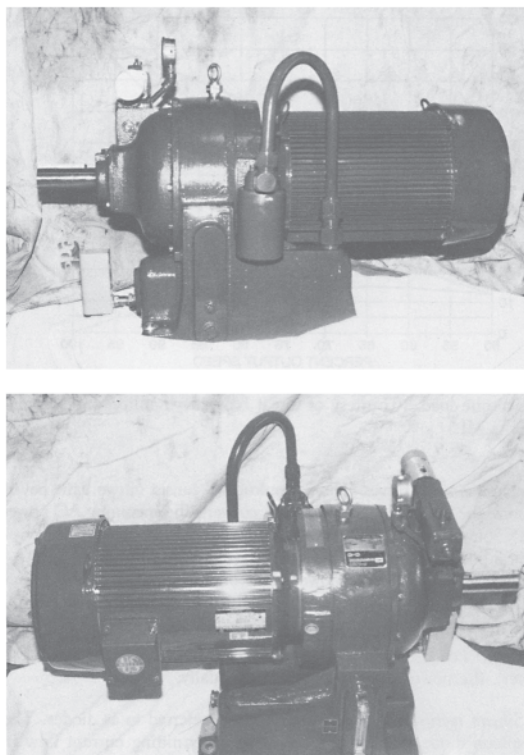


FIGURE 7.34 Assembly of a hydroviscous drive package. (Courtesy Great Lakes Hydraulics, Inc., Grand Rapids, MI.)

output speed can be regulated within $\pm 2\%$ of maximum speed. The torque transmitted by the drive is adjusted by changing the piston pressure.

This type of drive can be used for constant- and variable-torque applications and provides smooth operation at all speeds. The losses for these units include the slip loss that is common to all hydraulic drives and the fixed losses of the unit. [Figure 7.35](#) illustrates the performance of a hydroviscous drive driving a variable-torque load

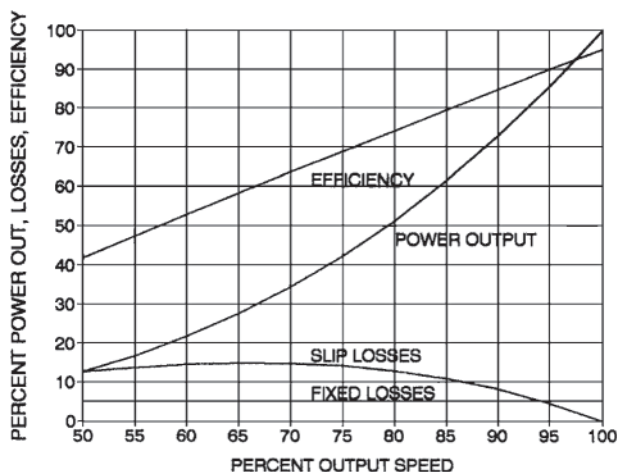


FIGURE 7.35 Performance of a hydroviscous drive system driving a variable-torque load. (Courtesy Great Lakes Hydraulics, Inc., Grand Rapids, MI.)

such as a centrifugal pump or fan; these data do not include the drive motor losses.

7.2.6 AC Variable-Frequency Drives

The squirrel-cage induction motor is normally considered a constant-speed device with an operating speed 2–3% below its synchronous speed. However, efficient operation can be obtained at other speeds if the frequency of the power supply can be changed. The synchronous speed of an induction motor can be expressed by

$$N_s = \frac{120f}{p}$$

where

N_s = synchronous speed, rpm

f = power supply frequency, Hz

p = number of poles in motor stator winding

A four-pole induction motor that has a synchronous speed of 1800 rpm when operated on a 60-Hz power supply operates at the following synchronous speeds as the power supply frequency is changed:

Power frequency, Hz	Motor synchronous speed, rpm
120	3600
90	2700
60	1800
30	900
15	450
7.5	225

Variable-Frequency Power Supplies. The utilization of power semiconductor technology has provided an economic means to generate a variable-frequency power supply from a fixed-frequency power source for industrial applications. Using the output of this variable-frequency semiconductor power system to supply three-phase power to a three-phase induction motor provides a means to vary the speed of the induction motor. Today, these systems are commonly identified as adjustable-frequency controllers or adjustable-frequency drives. These “controllers” consist of two basic power sections: the converter section, which converts the incoming AC power to DC power, and the inverter section, which inverts the DC power to an adjustable-frequency, adjustable-voltage AC power.

The size and types of power semiconductors used in the power sections of the controller depend on the voltage level, power level, and type of inverter.

CONVERTER POWER SECTION. In the converter power section (AC to DC power), the power semiconductors are usually

1. *Silicon rectifiers.* These are commonly referred to as diodes. The silicon diode has the characteristic of permitting current flow in one direction and blocking current flow in the opposite direction. These rectifiers, along with the silicon control rectifiers (SCRs), are the workhorses of the semiconductors for power conversion. They range in current rating up to 4800 A and voltage rating up to 5000 V. These devices have no control characteristics and are either conducting or blocking power.
2. *Silicon control rectifiers or thyristors.* The silicon control rectifiers block current flow in one direction and permit current flow in the opposite direction, much as the silicon diode does. Unlike the diode, however, the start of current flow can be controlled in the SCR. The SCR switches on and conducts current from the anode to the cathode when a proper voltage pulse is applied to the gate terminal. Current continues to flow until the device switches itself off. The SCRs have large power handling capability. They range in current rating up to 4000 A and in voltage ratings up to 4500 V. The rating of the device depends on the case temperature and duty cycle of the application.
3. *Gate turn-off thyristors.* The gate turn-off thyristor (GTO) is a semiconductor device that can be turned on like the thyristor (SCR) with a single pulse of gate current, but it can also be turned off by the injection of a negative gate current pulse. The GTO power losses are higher during switching, but elimination of forced commutation circuits improves the overall efficiency of the converter. In addition, GTOs are suitable for higher switching frequencies than SCRs. They are available with turn-off current ratings up to 3000 A as well as a blocking voltage capability up to 4500 V.

INVERTER POWER SECTION. In the inverter power section (DC power to AC power), the power semiconductors used depend on the type of inverter, voltage, and power ratings and may be any of the following:

1. *Silicon control rectifiers.* See above comments on SCRs. Because of their limited switching frequency, these devices are generally not used in pulse width modulation inverters.
2. *Gate turn-off thyristors.* See above comments on GTOs. Again, the frequency of operation is limited but is higher than the switching frequency of the SCR. GTOs have been used in pulse width inverters.
3. *Bipolar transistors.* These devices can be switched at higher frequencies than SCRs. However, the current ratings are limited; they may be on the order of 400 A rating, with VCEO ratings of 600 V, and 120 A rating, with 1000-V VCEO. Significant drive power is required for these devices.
4. *Bipolar Darlington.* These devices are generally two- or three-stage devices with built-in emitter-base resistances, speed-up diodes, and freewheeling diodes. The frequency of operation is typically in the 5- to 8-kHz range, but the devices can operate at higher frequencies, and the gain is considerably higher than for the bipolar transistor. Bipolar Darlington are available in the range of 140 A at 1400 V and 600 A at 1200 V. The units can be operated in parallel, and this is common practice in many inverters, with as many as four devices in parallel.
5. *Insulated gate bipolar transistors (IGBTs).* The IGBT combines on a single chip the high-impedance, voltage-controlled turn-on and turn-off capabilities of power MOSFETS and the low on-state conduction losses of the bipolar transistors. These devices can be switched at higher frequencies than the Darlington units and can be connected in parallel. They also have lower base-power requirements than the Darlington units. The ratings range up to current

rating I_c of 600 A and voltage V_{CES} of 1200 V. IGBTs are finding increased use in pulse width modulation inverters. The devices can be operated in parallel.

Figure 7.36 illustrates the relative rating of some of these power semi-conductor devices. The Darlington transistors and the IGBTs can be switched at frequencies above the range of human hearing. In addition, they can be operated in parallel. The types of power semi-conductor devices used in a particular type of inverter can change as the quality, capacity, and cost of existing devices and new devices improve.

Types of AC Inverters. The AC three-phase induction motor can be used for adjustable-speed applications when the power to the motor is supplied by a variable-frequency power supply (inverter).

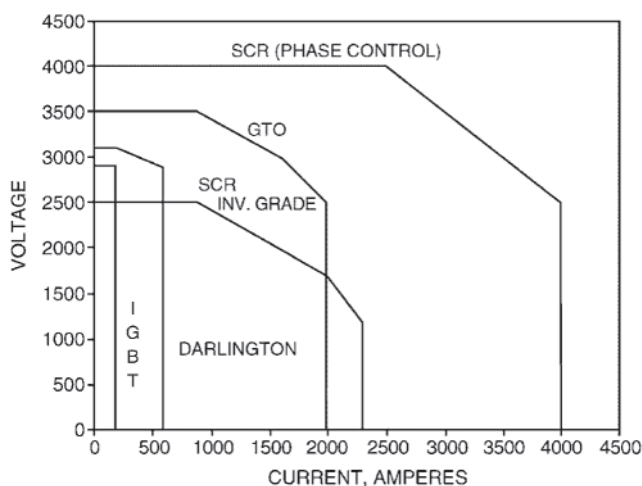


FIGURE 7.36 Relative rating range of various power semiconductor devices. (Courtesy Powerex, Inc., Youngwood, PA.)

The input voltage to the motor is varied proportionally to the frequency, i.e., at constant volts/hertz. At low frequencies, however, the voltage may be increased above its proportional level to obtain adequate torque. The torque developed by the induction motor is proportional to the magnetic flux in the motor air gap and to the rotor slip. As the frequency is decreased, the reactance of the motor decreases so that the applied voltage must be decreased proportionally to the frequency decrease to maintain constant air gap flux. If the applied voltage is not decreased, the motor magnetic circuit becomes saturated and there are excessive motor losses. At normal frequencies, the stator winding resistance drop is only a small percentage of the stator voltage drop so that the difference between the applied voltage and the net air gap voltage is relatively small. However, since the stator resistance is constant as the frequency is decreased and the reactance decreases proportionally to the frequency, the stator resistance drop voltage becomes a high percentage of the applied voltage. This results in a

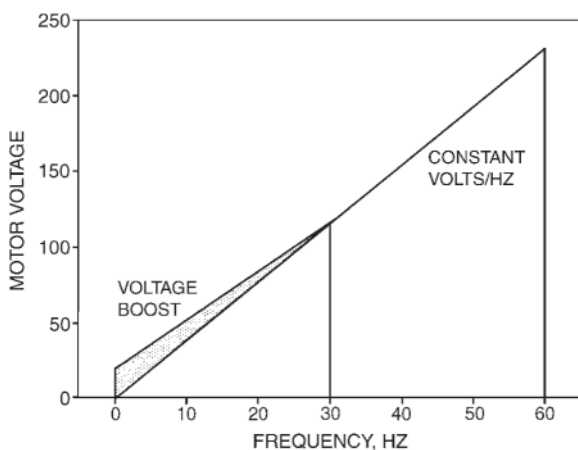


FIGURE 7.37 Typical voltage boost compared to constant volts/hertz motor voltage.

decrease in the net air gap voltage and air gap flux. Therefore, at lower frequencies (about 10 Hz and lower), to compensate for this increased stator resistance voltage drop and maintain the flux in the air gap, the applied voltage must be increased above the constant volts/hertz level. Figure 7.37 shows the typical voltage boost compared to constant volts/hertz at the lower frequencies. The amount of voltage boost should be limited so that the current drawn by the motor does not exceed 150% of the current rating of the adjustable-frequency power supply. If a higher motor current is needed to achieve the necessary starting torque, a higher current-rated adjustable-frequency power supply will be required. This high-voltage boost should be maintained only during the starting of the motor to protect both the drive motor and the inverter from damage. A number of inverter types are used in adjustable-frequency power supplies, but the most common types are

- Voltage-source inverters
- Current-source inverters
- Pulse width modulation inverters
- Vector control inverter systems

VOLTAGE-SOURCE INVERTER. Figure 7.38 illustrates the basic power circuit for a variable-voltage-source, six-step inverter. In this system, the 60-Hz input voltage is converted to a DC adjustable voltage by means of a three-phase semibridge converter. Then, by

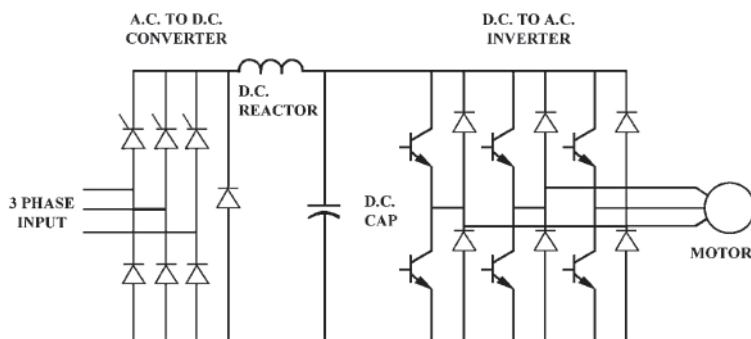


FIGURE 7.38 Voltage-source inverter.

means of a DC-to-AC transistor inverter, each of the three-phase output lines is switched from positive to negative for 180° of each 360° cycle. The phases are sequentially switched at 120° intervals, thus creating the six-step line-to-neutral voltage, or square wave line-to-line voltage, as shown in Fig. 7.39. The DC power supply is normally controlled by SCRs in the bridge rectifier, and an LC filter is used to establish a stiff DC voltage source. The output frequency is controlled by a reference signal that sets the control logic to achieve the correct gate or base-drive signals for the semiconductors in the inverter section. The semiconductors in the inverter section can be SCRs, GTOs, transistors, or Darlington transistors.

Speed control beyond the 10:1 range becomes a problem with the six-step inverter because at low voltage and frequency the harmonic currents become excessive, causing motor heating, torque pulsations, and cogging.

Advantage of the voltage-source inverter include

- Inverter section can use SCRs, GTOs, or transistors.
- Low switching frequency devices can be used.
- It is the simplest regulator.
- Standard or energy-efficient motors can be used with proper derating.

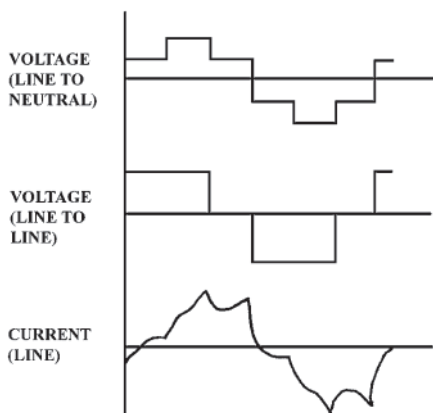


FIGURE 7.39 Voltage-source inverter wave shapes.

- It has multimotor capability.
- Voltage stress on motor insulation system is low.

Disadvantages of the voltage-source inverter include

- Poor input power factor that decreases with decreasing output frequency
- Harmonics fed into the 60-Hz AC supply system
- Limited speed control beyond the 10:1 range
- Torque pulsations and cogging
- High-harmonic currents, causing excessive motor heating

CURRENT-SOURCE INVERTER. In contrast to a stiff voltage source as in a voltage-source inverter, the current-source inverter has a stiff DC current source at the input. This is generally accomplished by connecting a strong inductive DC filter reactor in series with the DC source and controlling the voltage within a current loop. Figure 7.40 illustrates the power circuit for the current-source inverter. A three-phase bridge consisting of six SCRs converts the AC input to DC, and a three-phase bridge autosequential-commutated inverter inverts the DC to the AC output voltages. With a stiff current source, the output current waves are not affected by the load. The power semiconductors in the current-source inverter

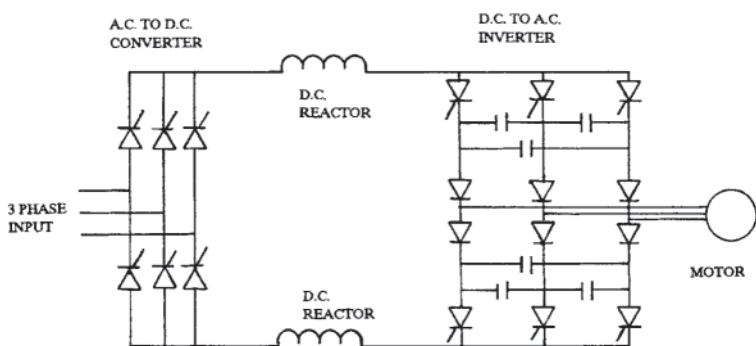


FIGURE 7.40 Current-source inverter.

have to withstand reverse voltages; therefore, devices such as transistors and power MOSs are not suitable. Figure 7.41 illustrates the waveforms for the current-source inverter. Note the high spikes in the line-to-neutral voltage.

Advantages of the current-source inverter include

- Simple SCR-type circuit
- Low-frequency inverter switches
- Inherent short-circuit capability
- Inherent regeneration capability
- Rugged construction

Disadvantages of the current-source inverter include

- Motor and control must be matched.
- Not suitable for multimotor operation.
- Poor input power factor.
- Low-speed torque pulsations and cogging.
- It can cause high-voltage spikes at the motor.

Current-source inverters have been developed using GTO devices and pulse width modulation to overcome some of the disadvantages of the current-source inverter.

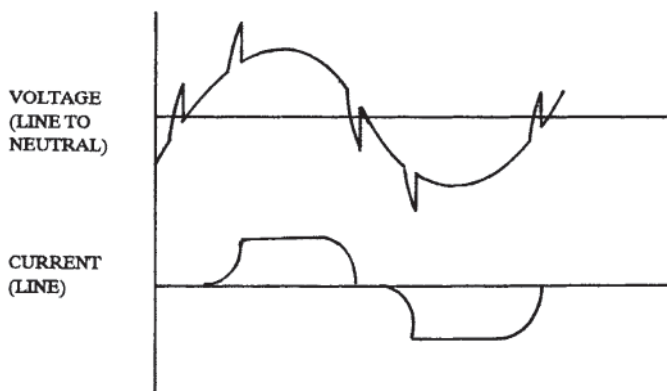


FIGURE 7.41 Current-source inverter wave shapes.

PULSE WIDTH MODULATION INVERTERS. In the pulse width modulation (PWM) system, the input AC power is rectified to a constant potential DC voltage. The DC voltage is then applied to the motor in a series of pulses. A number of methods have been devised to control the pulse width and to vary the frequency of the pulses as the motor speed is changed. In some cases, at the higher speed, the system becomes a six-step inverter.

Figure 7.42 shows the power circuit for a PWM inverter with a diode bridge to convert the AC voltage to DC voltage and a transistor DC to AC inverter to generate the AC output voltage.

The technology of pulse width modulation is not new. However, the use of microprocessors to provide improved modulation techniques and higher-speed switching power semiconductor devices such as transistors and IGBTs are making the PWM inverter the standard inverter in the 1- to 500-hp range.

A number of pulse width modulation procedures are used in today's PWM inverters. Some of these are

- Sinusoidal with a sine wave signal and a triangular carrier wave
- Harmonic elimination, particularly the fifth, seventh, eleventh, and thirteenth harmonics

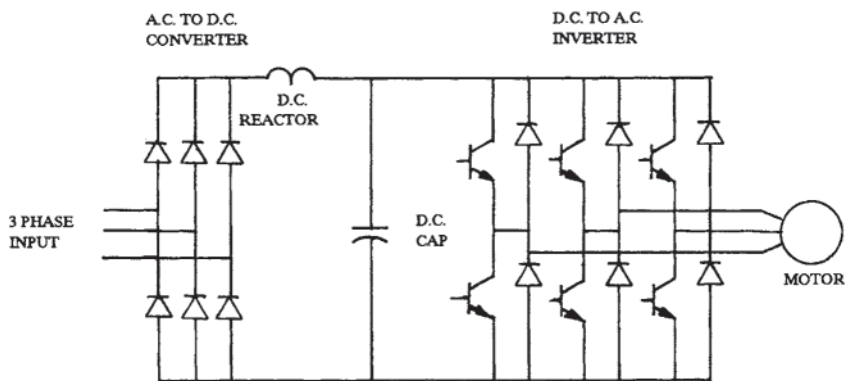


FIGURE 7.42 Pulse width modulation inverter.

- Distortion minimization with five switching angles/quarter cycle
- Minimum ripple current
- Uniform sampling

The ideal PWM system balances the switching losses in the inverter with the current and torque ripples and the heating losses in the drive motor for the best overall performance (Figure 7.43).

By selecting the width and spacing of the pulses, lower-order harmonics, such as the fifth, seventh, and eleventh, can be eliminated in the waveform. If the pulse rate is high enough, the motor inductance presents a high impedance so that the pulse-rate-frequency current is insignificant. From the motor viewpoint, it is desirable to have a high-frequency pulse rate. From the inverter viewpoint, since most of the losses occur during switching, it is best to have a low

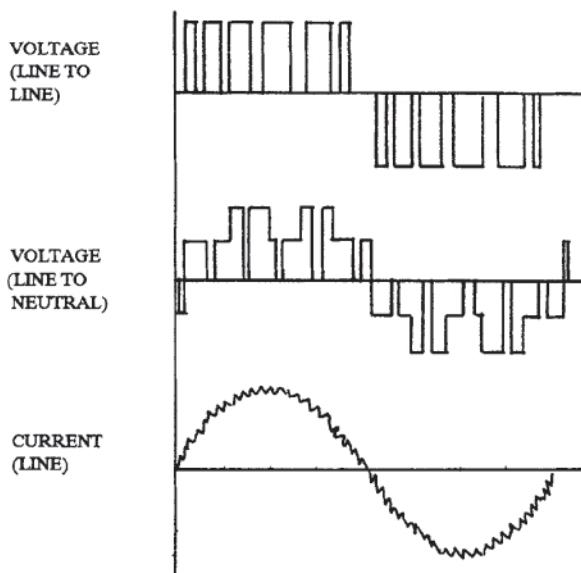


FIGURE 7.43 Pulse width modulation inverter wave shapes.

pulse rate. However, the number of pulses per cycle must be maintained high enough to avoid troublesome harmonics that may be resonant with the motor components and cause noise and vibration in the drive. The switching and recovery time of SCRs limits their use on PWM systems. IGBTs, power transistors, Darlington transistors, and GTOs have faster switching times with lower losses, and so they are used at the higher pulse rates required for smooth operation. While the PWM inverters improve the waveforms by eliminating the low-order harmonics, they impose a series of high-voltage impulses on the motor winding. Although the winding inductance smooths the current waveform, the rapid voltage changes produce insulation stresses on the first few turns of each of the motor windings. Full-voltage PWM systems produce the most severe stresses, particularly at low speeds, where the motor back-EMF is low.

Advantages of PWM inverters include

- Wide speed range.
- Smooth low-speed operation.
- Multimotor operation.
- Standard or energy-efficient motors can be used with proper derating.
- Minimum problems matching motor and inverter.
- High-input power factor.

Disadvantages of PWM inverters include

- Complex control
- Requires high-frequency power semiconductors in the inverter
- Higher motor heating and noise (depends on the modulation system used)
- Not regenerative
- Imposes high-voltage gradients on the motor insulation system

There are numerous variations of these three types of adjustable-frequency inverters, but the principle of operation is essentially the same. As with any product, changes and improvements are being

accomplished every day. The improvements come primarily from the increasing use of integrated circuits as well as microprocessors, which have greatly reduced the number of control logic components. Also the use of power IGBTs, power transistors, and GTOs has reduced the cost of power elements. These factors, plus improved designs and techniques, have reduced and will continue to reduce the size and cost of the inverters. At the same time, performance and reliability continue to improve.

VECTOR CONTROL INVERTER SYSTEMS. One important variation or addition to the previously discussed inverter systems is the vector control inverter system. Vector control considers the analogy between AC and DC electrical machines. The ultimate object of the vector control system is to control the AC induction motor as a separately excited DC motor is controlled, i.e., to control the field excitation and torque-generating currents separately and independently. To control the induction motor in this manner, the air gap flux (net air gap voltage) and rotor current must be separately controlled. The vector control drives available are based mostly on the indirect flux control method. The magnitude, frequency, and phase of the stator current components are controlled as a function of the rotor position, slip frequency, and torque command. Figure 7.44 is a block diagram of a vector

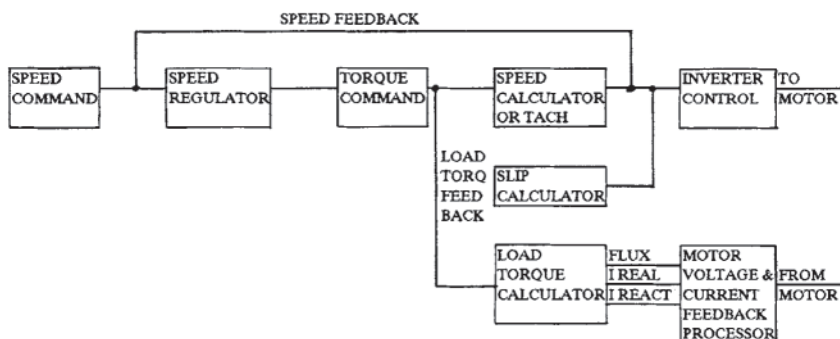


FIGURE 7.44 Block diagram of vector control logic.

control logic system, with the input signals received from the motor and the output control signal from the vector control system supplied to the inverter section of a PWM inverter. The excitation current component and the torque component of the current are calculated from the motor terminal voltage and current and the motor speed. The performance of this method of control depends on how closely the algorithm of the vector system matches the induction motor characteristics. The precision of the system also depends on the precision of the tachometer or rotor speed sensor since the slip control is based on this signal. Without a tachometer or rotor speed sensor, the precise speed range is 20:1, with the speed

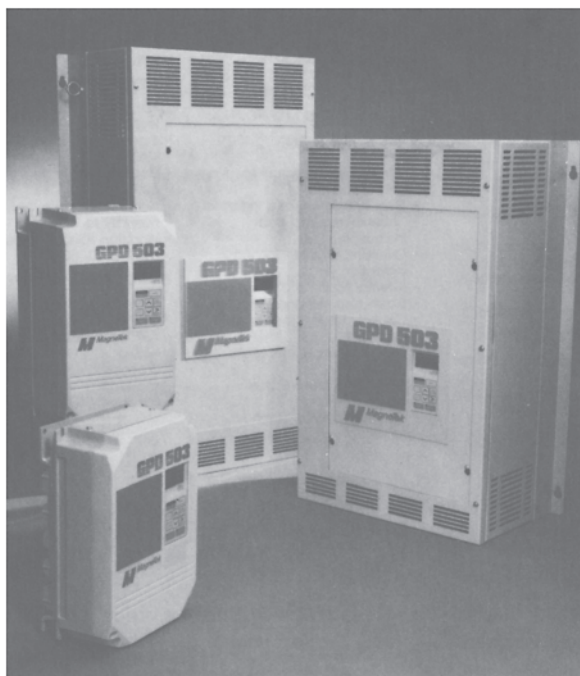


FIGURE 7.45 Family of PWM adjustable-frequency power supplies. (Courtesy Magnetek, New Berlin, WI.)

within $\pm 0.5\%$ accuracy and an allowable operating range of 50:1. With a precision rotor speed or position sensor, the operating range can be extended to 200:1, with a speed within $\pm 0.1\%$ accuracy. Closer speed regulation can be obtained with more precise rotor sensing. This system can be used with either voltage-source or current-source inverters with a PWM inverter section.

These systems have been used mainly on servosystems and machine tool applications, but are being used in more industrial application to replace DC adjustable-speed drives.

Inverter Features. The available range of features and rating of adjustable-frequency drives has expanded extensively in recent years. Figure 7.45 shows a family of Magnetek adjustable-frequency systems. These units are PWM units with an insulated-gate bipolar transistor in the inverter section. The range in rating for these units is 1–40 hp at 230-V input and 1–75 hp at 460-V input. Units are also available with transistors in the inverter section in the range of 1–125 hp at 230-V input and 1–600-hp input at 460-V input.

The control and protection features available for this product line, which is typical of many adjustable-frequency systems, are shown in Fig. 7.46.

In addition to the usual protection features, a variety of adjustments are available, including the following:

- Adjustable acceleration and deceleration rates.
- Torque limit control.
- Stall protection.
- Critical frequency rejection. Generally, three prohibited frequencies can be selected to prevent the drive system from operating at a resonant speed at speeds within the operating speed range.
- Selectable volts/hertz pattern. Normally, the output of the inverter section is based on constant volts/hertz. However, to provide for application variations, such as induction motor rating, high starting torque, variable-torque loads, and operation at different frequency ranges, provision is made for different volts/hertz patterns. Figure 7.47 illustrates

STANDARD FEATURES

- Frequency resolution 0.1 Hz with digital reference; 0.06 Hz with analog reference
- Frequency regulations 0.01% with digital command; 0.1% with analog (15 to 35° C)
- Standard Frequency range 1.5 to 800 Hz
- Volts/Hertz ratio, 15 preset patterns, one fully adjustable pattern
- Independent accel/decel 0.1–6000 sec.
- DC injection braking amplitude & duration, current limited
- Signal follower external bias & gain
- Critical frequency rejection, 3 selectable
- Torque limit, 30–150%
- Jog speed, adjustable zero to 100%
- Multi-speed setting, 9 possible
- Forward/reverse operation
- Speed range 40:1
- NEMA 1 enclosure (NEMA 12 optional)

- 24 VDC Logic
- Run/fault contacts 1 amp, 250 VAC or 30 VDC
- Remote speed reference capability 0–10 VDC (20K ohms) or 4–20 mA (250 ohm)

PROTECTION and MONITORING

- Overload capability to 150% rated, 60 sec.
- Instantaneous overcurrent trip and indication
- Overvoltage trip and indication
- Undervoltage trip and indication
- Overtemperature trip and indication
- External fault trip and indication
- Blown fuse trip and indication
- Control circuit error trip and indication
- DC bus charge indication
- DC bus fuse
- Ground fault protection
- Stall prevention
- Electronic motor overload protection

- Momentary power failure ride-through (2 sec. 5 HP and above); (0.2 sec. below 5 HP with option of 2 sec.)

ENVIRONMENTAL CONDITIONS

- Altitude to 3300 feet above sea level
- Operating ambient temperature –10 to 40° C
- Storage temperature –20 to 60° C
- Noncondensing relative humidity to 90%
- Vibration 1G max under 20 Hz; 0.2G at 20–50 Hz

INPUT POWER REQUIREMENTS

- 230V model for 200, 208, 220 or 230 VAC, $\pm 10\%$
- 460 V model for 380, 400, 415, 440, or 460 VAC, $+10\%$
- 3-phase, 3-wire, phase sequence insensitive
- Frequency 50 or 60 Hz, $\pm 5\%$

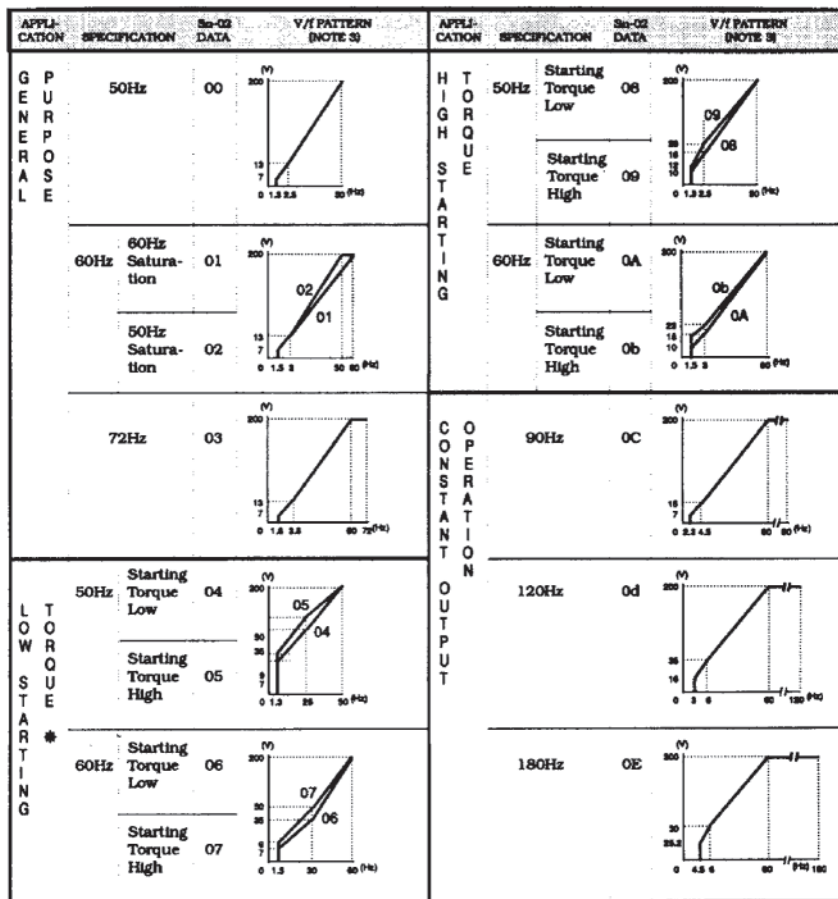
FIGURE 7.46 Typical features of PWM adjustable-frequency power supplies. (Courtesy Magnetek, New Berlin, WI.)

the types of volts/hertz patterns that can be selected. In addition, some units automatically select the optimum voltage for a given frequency and load condition.

- Automatic carrier frequency. As the motor load increases, or the operating frequency decreases, the carrier frequency will automatically increase; this increase in the carrier switching frequency reduces the output current harmonics and, as a result, provides more motor torque per ampere.

7.2.7 AC Variable-Frequency Drive Application Guide

Unfortunately, the selection and application of an AC variable-frequency induction motor drive system are more complex than the



NOTES: *Use of these patterns is NOT RECOMMENDED. Consult MagneTek for assistance.

1. The following conditions must be considered when selecting a V/f pattern: —Pattern matches the voltage-frequency characteristics of the motor. —Maximum motor speed.
2. V/f pattern for high starting torque should be selected for: —Wiring distance. —Large voltage drop at start. —AC reactor connected to GPD 503 input or output. —Use of motor rated below GPD 503 max. output.
3. Patterns shown are for 200 V input; for other input, multiply all V values by $V_{IN}/200$. Example: For 400 V input, multiply by $400/200 = 2$.

FIGURE 7.47 Typical standard (preset) volts/hertz patterns. (Courtesy Magnetek, New Berlin WI.)

selection of a fixed-speed induction motor. The duty cycle of the inverter-motor combination must be checked at all load conditions to make certain that the particular drive combination is suitable for the given application. In addition, some applications may require control options such as digital speed control, closed-loop speed control, frequency metering, variable-voltage boost, or remote signal inputs such as pressure or temperature. The characteristics that determine the appropriate drive combination are the following:

1. Speed range required
2. Speed-torque characteristics of the load
3. Load inertia
4. Load acceleration and deceleration times
5. Required operating time at various speeds
6. Inverter output waveform and its approximate harmonic content
7. System efficiency over the operating range
8. Regenerative energy dissipation in the inverter
9. Motor temperature rise at the required duty cycle and the voltage-to-frequency ratio provided by the inverter
10. Motor rating based on the duty cycle
11. Motor insulation life derating for its input waveform (applies to full-voltage PWM systems)
12. Inverter construction and enclosure
13. Motor enclosure

When applying adjustable-frequency induction motor systems, the characteristics of both the motor and the power supply must be considered as an integrated system. The constraints imposed on the induction motor must be considered in selecting both the motor and the inverter.

The adjustable-frequency power supply has a constant ratio of volts/hertz. As the output frequency and voltage are changed, the induction motor speed changes proportionally to the output frequency. Since the induction motor reactance is proportional to the frequency, the output voltage must also decrease in the same ratio to maintain a constant air gap flux. If a constant slip rpm is

maintained, the induction motor is essentially a constant-torque motor. For example, consider a four-pole induction motor that, when supplied with 60-Hz power, produces its rated torque at 1750 rpm, or a slip of 50 rpm. When the motor is supplied with 30-Hz power at constant volts/hertz, it will produce rated torque at 50-rpm slip, or $900 - 50 = 850$ -rpm output speed. When the motor is supplied with 10-Hz power at constant volts/hertz, it will again produce rated torque at 50-rpm slip, or $300 - 50 = 250$ -rpm output speed.

A conventional speed-torque curve exists for the induction motor at each frequency it operates at, as shown in [Fig. 5.13](#). However, because of the 150% current limitation of the power supply, the maximum torque available is reduced as shown in [Fig. 5.14](#). This reduced available torque and the time constraint of the 150% current limitation (usually for 60 sec) must be considered in the acceleration and deceleration of the load. This is particularly important for high-inertia loads. The locked-rotor or starting torque available is also limited by the current constraints of the power supply and the characteristics of the induction motor. At low frequencies below 10 Hz, voltage boost above the constant volts/ hertz level may be required to start the load. This increase in voltage can cause excessive currents in both the motor and power supply and should be maintained for a minimum time. [Figure 5.15](#) shows the locked-torque characteristics for a 10-hp motor at low frequencies, including the effect of voltage boost on the locked-rotor torque. The determination of the starting torque and accelerating torque are essential for the proper selection of the adjustable-frequency power supply and the drive motor.

These restrictions are often overlooked in the conversion from a fixed-speed drive to an adjustable-frequency motor drive system. Similarly, in the conversion from a mechanical variable-speed drive to an adjustable-frequency induction motor drive, the torque requirements must be determined. In many instances, the torques the mechanical drive can develop at low speeds and at starting exceed the torques available on the same rated horsepower adjustable-frequency drive.

Once the torque requirements have been established, the sizing of the induction motor must be based on the limiting temperature

rise of the motor. The items that influence the temperature rise are operating speed range, type of load, motor losses, and type of motor enclosure. The induction motor losses, including the harmonic losses when the motor is operating from an adjustable-frequency power supply, must be balanced against the heat-dissipation ability of the motor. [Figures 5.18](#) and [5.19](#) illustrate the increase in the induction motor losses at constant torque when supplied by a nonsinusoidal power source. In contrast, [Fig. 5.21](#) shows the decrease in the heat-dissipation ability of the induction motor as the operating frequency is decreased. [Figure 5.22](#) shows the influence of the harmonic losses on the temperature rise of a 5-hp induction motor at various operating frequencies.

Most manufacturers of electric motors have guidelines on the heat-dissipation capabilities of their motors at various speeds and types of loads.

[Chapter 5](#) suggests some guidelines on the derating of motors for various types of applications when supplied by adjustable-frequency power systems.

Most adjustable-frequency power systems are provided with means to adjust the volts/hertz ratio and to provide a voltage boost when required. However, the lowest possible volts/hertz setting for satisfactory system operation should be selected. Unnecessarily high volts/hertz settings reduce the induction motor efficiency, increase the losses, and increase the motor temperature rise and noise level. Some adjustable-frequency power systems automatically adjust the voltage to the optimum level of motor operation. [Figure 7.48](#) shows a comparison of the efficiencies for a 10-hp induction motor driving a variable-torque load at constant volts/hertz and at the optimum voltage for each frequency. In this case, the figure also shows the optimum voltage as a percent of the constant volts at each frequency of operation. Note that the voltage was maintained at constant volts/hertz down to about 45 Hz since there was no improvement in performance obtained by decreasing the voltage below constant volts/hertz.

If energy saving is the main justification for a drive, then the overall efficiency must be considered, including both the motor and adjustable-frequency power supply. The inverter efficiency varies with the load and operating frequency. The motor efficiency varies

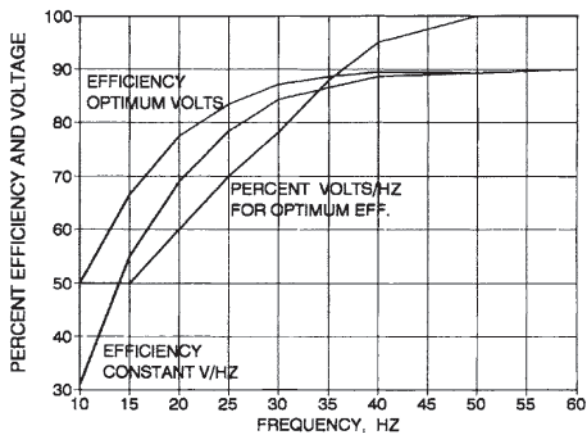


FIGURE 7.48 Improvement in the efficiency of a 10-hp, energy-efficient, four-pole induction motor by reducing the volts/hertz when supplying a variable-torque load.

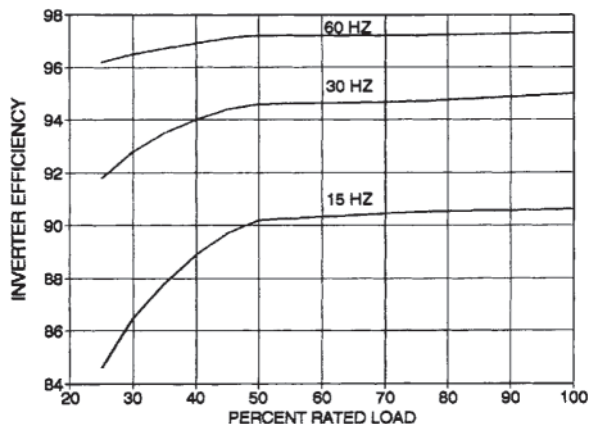


FIGURE 7.49 Adjustable-frequency power supply efficiency as a function of load and output frequency.

with the load and the operating frequency, and there are additional losses in the motor as a result of the harmonics in the motor supply frequency. Figure 7.49 shows the efficiency of an adjustable-frequency power supply as a function of load and operating frequency. Figure 5.19 compares the efficiency of a 100-hp induction motor with a sinusoidal power supply and a nonsinusoidal power supply (such as an adjustable-frequency power source), reflecting the decrease in motor efficiency as a result of the harmonics in the supply voltage. The overall efficiency of the adjustable-frequency induction motor system is the product of the component efficiencies and is illustrated in Fig. 7.50. This figure also compares the induction motor efficiency when the motor is operating on a sine-wave power source to the overall efficiency when it is operating with an adjustable-frequency power system.

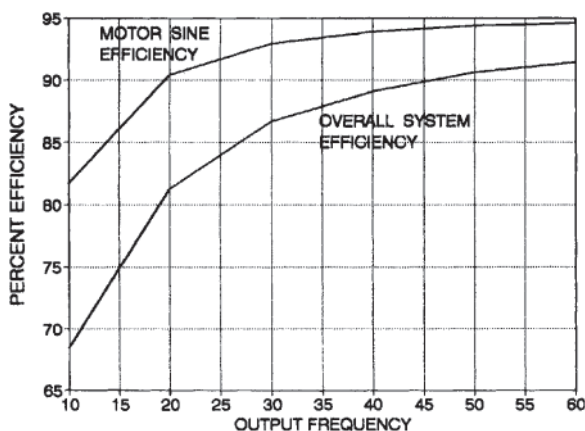


FIGURE 7.50 Efficiency of a 100-hp, energy-efficient induction motor with a constant-torque load on a sine-wave power supply versus the overall efficiency on an adjustable-frequency power supply.

The following is a summary of the types of loads suitable for application of adjustable-frequency induction motor systems:

- *Variable-torque loads*

- Centrifugal fans
- Centrifugal pumps
- Agitators
- Axial centrifugal compressors
- Centrifugal blowers

- *Constant-torque loads*

- Calenders
- Positive-displacement blowers
- Conveyers
- Centrifuges
- Reciprocating and rotary compressors
- Positive-displacement pumps
- Slurry pumps
- Cranes
- Elevators
- Mixers
- Printing presses
- Washers

- *Constant-horsepower loads*

- Drill presses
- Grinders
- Lathes
- Milling machines
- Tension drives
- Winders
- Recoilers

- *Impact loads.* The following types of impact loads may be suitable for application of adjustable-frequency induction motor systems but require special consideration of the adjustable-frequency power supply in order to provide the peak induction motor output torques required and stay within

the current limitations of the adjustable-frequency power supply.

- Lathes
- Milling machines
- Rolling mills
- Punch presses
- Shakers
- Shears
- Crushers

7.2.8 Wound-Rotor Motor Drives with Slip Loss Recovery (Static Kramer Drives)

The wound-rotor motor has normally been used for short-time duty applications such as cranes and hoists where torque control is of prime importance. When it has been used on continuous-duty installation, the major purpose has been to obtain controlled starting and acceleration. The reason for this limited use has been that high slip losses occur at speeds below normal operating speed. With the development of power electronics and solid-state inverters, systems have been developed to recover these slip losses.

These drives are commonly referred to as static Kramer drives. The original Kramer drives used a rotary converter instead of power semi-conductors and fed the power back to the line from a DC motor coupled to the induction motor. With the recovery of the rotor slip losses, the efficiency of the wound-rotor feedback system is comparable to the efficiency of an adjustable-frequency induction motor drive. It has an advantage in that the inverter has only to be large enough to handle the rotor slip losses. The system has the disadvantages, however, of the unavailability and high cost of the wound-rotor motor. Today, these systems are generally custom-designed for specific applications with a limited speed range, such as large pumps and compressors.

Figure 7.51 is a power circuit diagram for the static Kramer drive. As shown, the output of the wound rotor is connected to a three-phase rectifier bridge. The output of the bridge is connected to a

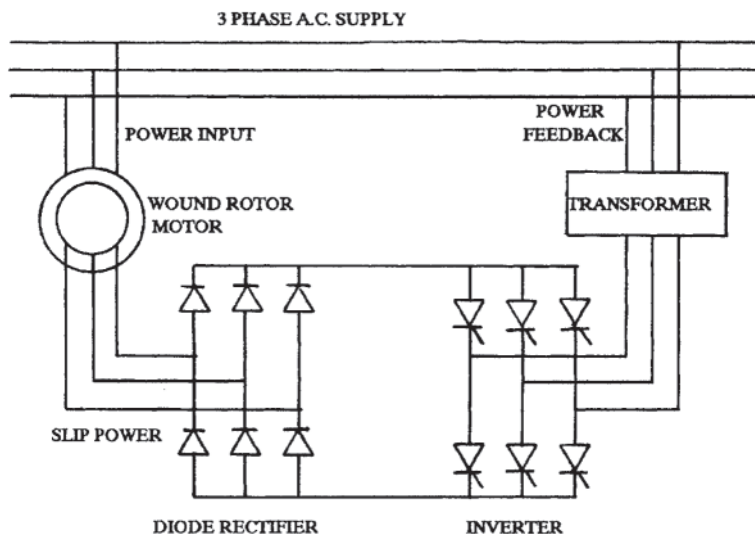


FIGURE 7.51 Static Kramer drive.

fixed-frequency inverter, the output of which is connected to the primary power supply that supplies the motor stator. The connection from the inverter output to the primary power supply is generally through a matching transformer. The effective rotor resistance, and hence the motor speed, is controlled by controlling the firing angle of the power SCRs in the inverter section.

The speed range that can be obtained is determined by the motor secondary (rotor) voltage; for instance, for a 100% speed range system,

480-V power supply: The rotor voltage must be 380 V or less.

600-V power supply: The rotor voltage must be 480 V or less.

and for a 50% speed range system,

480-V power supply: The rotor voltage must be between 600 and 760 V.

600-V power supply: The rotor voltage must be between 750 and 960 V.

For power supply voltages above 600 V, such as 2300 and 4160 V, the motor primary can utilize the line voltage. However, a matching transformer is required at the output of the rotor inverter, and it need only be large enough to handle the rotor losses, not the total motor input.

The efficiency of the controller is approximately 98.5% and is constant over the speed range; thus, the system is very efficient in recovering the slip losses and raising the system efficiency.

Consider a 200-hp wound-rotor motor on a pumping installation where the motor horsepower load is a cubic function of the speed. Without the slip recovery controller, at full speed (1764 rpm):

Horsepower output, 200 hp
Motor efficiency, 94%

At one-half speed (882 rpm):

Horsepower output, 25 hp
Motor efficiency, 46%

With the slip recovery controller, at full speed (1764 rpm):

Horsepower output, 200 hp
Motor efficiency, 94%
Overall system efficiency, 94%

At one-half speed (882 rpm):

Horsepower output, 25 hp
Motor efficiency, 46%
Overall system efficiency, 84%

Note that recovery of the slip losses at one-half speed increased the efficiency from 46 to 84%.

The wound-rotor motor with a slip recovery system used on a pump or fan application can usually be operated over a 50% speed range with self-ventilation. For applications requiring continuous operation below 50% speed, forced ventilation may be required for the motor.

This type of drive system offers an energy-efficient system comparable to adjustable-frequency systems and superior to slip-loss systems.

7.3 APPLICATIONS TO FANS

Various types of fans used to move air or other gases are among the largest consumers of electric power and among the largest users of integral-horsepower electric motors. In general, fans can be divided into two broad categories: centrifugal fans and axial flow fans.

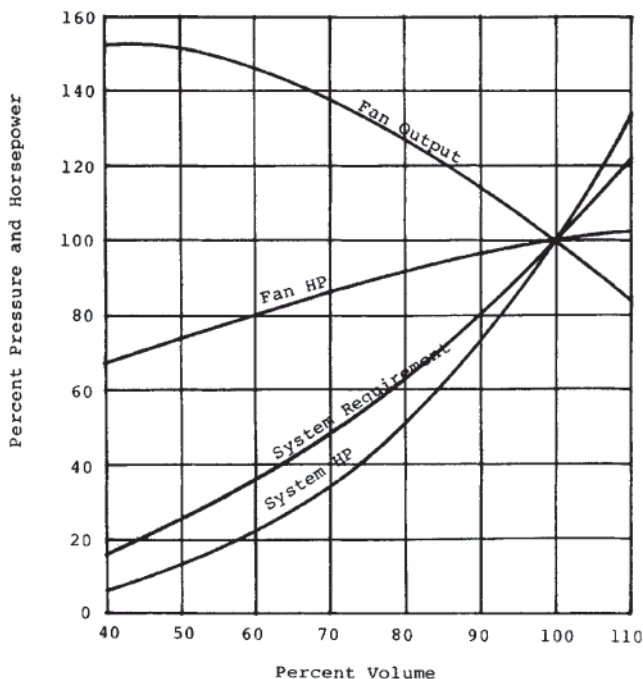


FIGURE 7.52 Sample application, characteristic fan data, and system characteristic.

The guide for selection of the proper fan for a given application is covered by most fan manufacturer catalog information. However, to obtain the most energy-efficient system, it is necessary to examine the methods of controlling airflow in a given system.

First, it is necessary to determine the system resistance characteristic for various airflow rates. A curve can be developed for the system in terms of the air volume versus the static pressure required. This curve generally follows a simple parabolic law in which the static pressure or resistance to airflow varies as the square of the volume of air required. [Figure 7.52](#) shows the system curve for a specific example that will be discussed later.

Next is the selection of the type of fan. Many of the applications in general heating, ventilating, and air conditioning systems involve centrifugal fans. These fans generally fall into three major categories based on the type of impeller design:

1. *Backward-curved blades.* The horsepower reaches a maximum near peak efficiency and becomes lower toward free delivery. [Figure 7.53](#) is the typical performance curve for the backward-curved fan. The volume is the percent of free-flow volume, and the pressure is the percent of static pressure at zero volume. The horsepower is the percent of maximum horsepower.
2. *Radial blades.* These have higher-pressure characteristics than the backward-curved fan. The horsepower rises continually to free delivery. [Figure 7.54](#) is the typical performance curve for radial-blade fans.
3. *Forward-curved blades.* The pressure curve is less steep than that for the backward-curved fan. The peak efficiency is to the right of the peak pressure. The horsepower rises continually to free delivery. [Figure 7.55](#) is the typical performance curve for forward-curved fans.

The size and type of fan selected should be such that the fan is operating near its peak static efficiency for the maximum flow rate required. The performance of the fan at other speeds will follow the following fan laws:

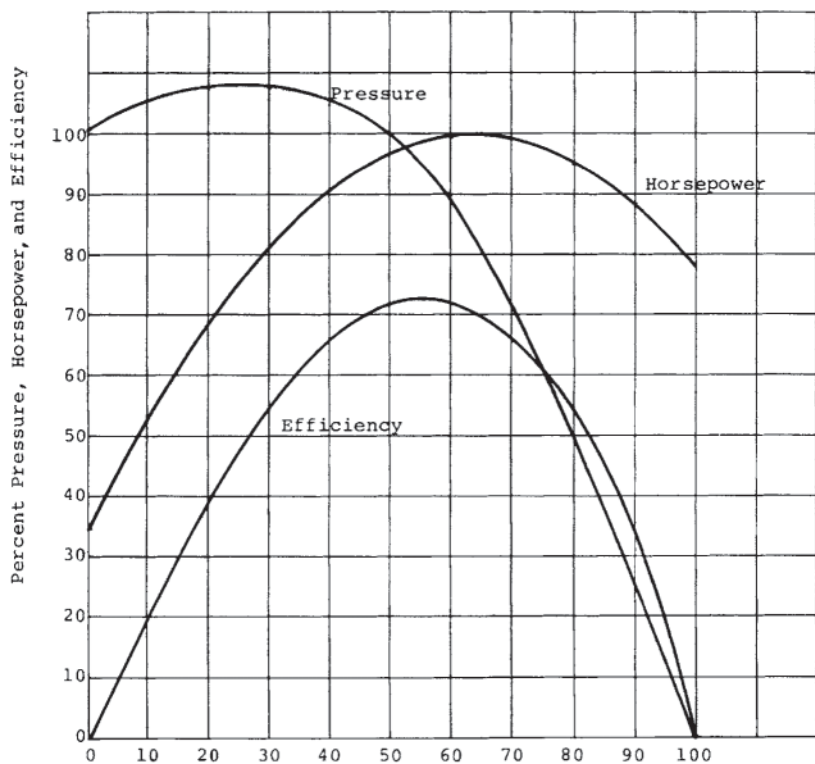


FIGURE 7.53 Characteristic curves for the backward-curved fan.

1. The volume V of air varies as the fan speed.
2. The static pressure P varies as the square of the fan speed.
3. The horsepower varies as the cube of the fan speed.

$$\text{Static efficiency} = \frac{VP}{6369 \times \text{hp}}$$

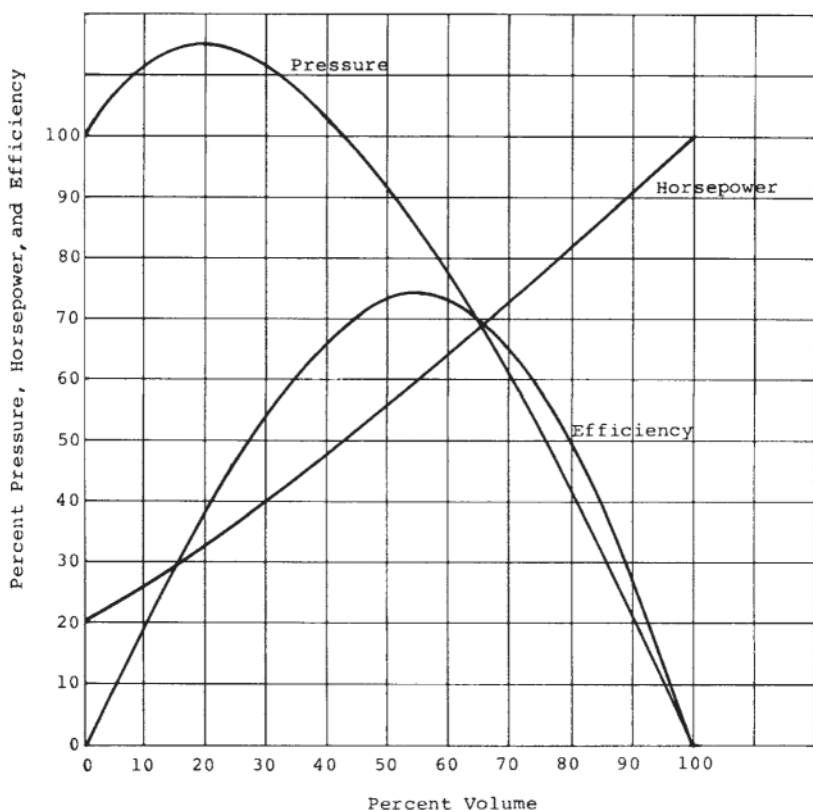


FIGURE 7.54 Characteristic curves for the radial fan.

Several methods of controlling the airflow can be considered:

- Damper control
- Variable inlet vane control
- Hydrokinetic or fluid-drive systems
- Eddy current drive systems
- Mechanical variable-speed drive units
- AC variable-frequency systems
- Wound-rotor motor with slip recovery systems
- Two-winding, two-speed motors

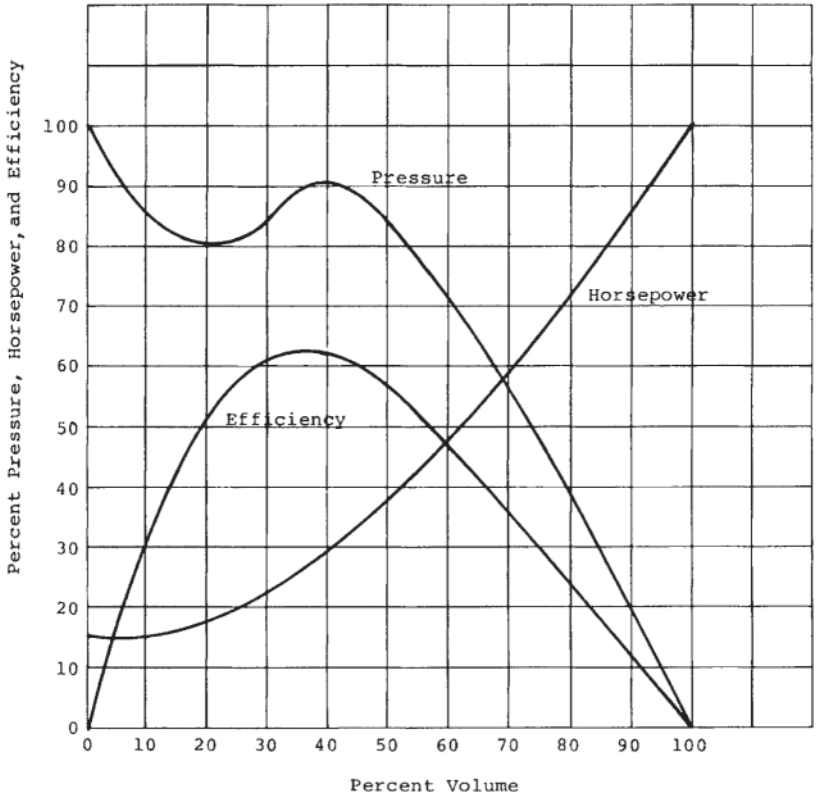


FIGURE 7.55 Characteristic curves for the forward-curved fan.

The comparison of these systems is best illustrated by an example.

EXAMPLE

The characteristic curves of the fan and air system for the example are shown in Fig. 7.52. The data have been shown in percentages of the pressure, volume, and horsepower at the balanced point at which the system resistance curve and the fan curve intersect.

Based on this fan-system curve, the horsepower input at the fan to produce the airflow is also shown. Figure 7.56 shows the input horsepower required for each of the preceding systems compared to the fan horsepower required as the airflow requirement is varied between 40 and 100% volume.

To determine the most energy-efficient system, the operating cycle, i.e., the percent time operating at each volume flow, must be determined; then the energy savings and net present worth of each system can be compared to the most inefficient system, i.e., one using a discharge damper.

To illustrate these data, three different operating cycles have been assumed with the following data:

Horsepower at full air volume, 100 hp
 Annual operating hours, 4000 hr
 Initial power rate, \$0.06/kWh
 Annual increase in power rate, 10%
 Cost of money, 15%
 Tax rate, 40%
 System life, 10 yr

The operating cycles are as follows:

Cycle	Time at each air volume, %		
	100% air vol.	80% air vol.	60% air vol.
I	75	15	10
II	33	33	34
III	10	15	75

Two other operating cycles based on fixed-speed operation at two speeds using a two-winding, two-speed motor with an 1800/ 1200-rpm speed combination are as follows:

Operating cycle 1-A:

100% (full) air volume: 75% of the time
 66% air volume: 25% of the time

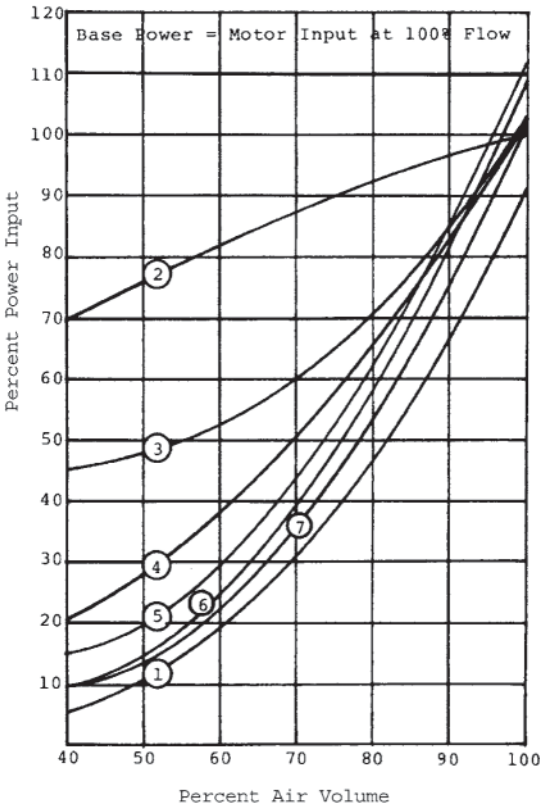


FIGURE 7.56 Power input for adjustable-flow systems: (1) fan horsepower required, (2) damper control, (3) inlet vane control, (4) hydrokinetic and eddy current system, (5) mechanical varispeed system, (6) variable-frequency system, (7) wound rotor with rotor loss recovery system; 100% power is the power input to the motor at 100% airflow.

TABLE 7.2 Comparison of Annual Kilowatt-Hour Savings for Adjustable Flow Fan Systems^a

Operating cycle	System					
	Multispeed motor	Variable vane inlet	Fluid drive or eddy current drive	Mechanical varidrive	Variable-frequency system	Wound rotor with slip recovery
I	—	10,431	15,080	4,070	12,550	32,768
II	—	51,515	71,916	81,355	87,879	103,008
III	—	80,382	118,948	141,854	148,216	157,834
I-A	39,396	—	—	—	—	—
III-A	129,060	—	—	—	—	—

^a Base for comparison: damper control.

Operating cycle 1-B:

100% (full) air volume: 25% of the time

66% air volume: 75% of the time

The summary of the annual power savings in kilowatt-hours for each system is shown in [Table 7.2](#). The net present worth of the energy savings based on the defined assumptions is shown in [Table 7.3](#). This summary shows the influence of the operating cycle on the power savings and the net present worth of those savings. When compared to the first cost of each system in conjunction with other considerations, including reliability, flexibility, maintenance, and environment, this net present worth will provide an economic basis for selecting the most cost-effective system.

7.4 APPLICATIONS TO PUMPS

Pumps are the largest user of electric motors in the integral-horsepower sizes 1 hp and larger. The selection and application of electric motors and adjustable-speed systems to pumps become very complex and difficult because of the large numbers of types of pumps and their lack of standardization. The pumps fall into two broad categories: displacement pumps and dynamic pumps. The dynamic pumps include noncentrifugal and centrifugal types. The highest percentage of the pumps used for industrial processes are of the centrifugal type; therefore, the discussion in this section will be limited to drive applications of this type.

In the selection of a pump for a given system, the system characteristics must be determined in terms of flow rate in gallons per minute versus total head, in feet, under all flow rates expected. The system should include an allowance for pipe corrosion and other factors that affect the system characteristics. The pump then selected should be sized to the system characteristic at the maximum flow rate such that the efficiency is close to the optimum for the pump. Then, for an adjustable-speed system, it is necessary to check the pump performance at the minimum flow point required.

The various pump manufacturers provide data for their pumps and also provide assistance in selecting the correct pump for the

TABLE 7.3 Net Present Worth Comparison in Dollars for Adjustable-Flow Fan Systems^a

Operating cycle	System					
	Multispeed motor	Variable vane inlet	Fluid drive or eddy current drive	Mechanical varidrive	Variable-frequency system	Wound-rotor motor with rotor loss recovery
I	—	3,558	5,143	1,388	4,271	10,176
II	—	17,571	24,528	27,746	29,973	35,029
III	—	27,416	40,569	48,381	50,551	53,831
I-A	13,727	—	—	—	—	—
III-A	44,018	—	—	—	—	—

^a Base for comparison: damper control.

application. The initial guide is a performance curve at a fixed speed, as shown in Fig. 7.57, indicating the best efficiency point on each pump in a family of pumps. For a given pump, detail performance curves such as those in Fig. 7.58 are available from the manufacturer.

The following relationship applies to pumps (as discussed for fans in Sec. 7.3):

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2}$$

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2} \right)^2$$

$$\frac{\text{BHP}_1}{\text{BHP}_2} = \left(\frac{N_1}{N_2} \right)^3$$

$$\text{BHP} = \frac{QH \times \text{Sp. Gr.}}{3960 \times \text{Pump Eff}}$$

$$\text{Pump Eff} = \frac{QH \times \text{Sp. Gr.}}{3960 \times \text{BHP}}$$

where

Q = capacity, gpm

H = total head, ft

BHP = brake horsepower

N = pump speed, rpm

Sp. Gr. = specific gravity of liquid

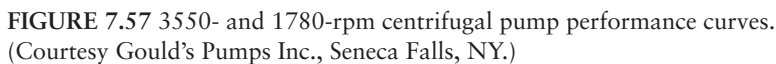
To illustrate the application and cost analysis of various methods of flow control, consider an example comparing the following:

Throttling in the discharge line

Eddy current or hydraulic fluid drive systems

AC variable-frequency system

Wound-rotor motor with slip recovery system



Customer _____ Inquiry No. _____ Date _____
 Service _____ Item No. _____ P.O. No. _____ Date _____
 F.O. No. _____ ; _____ GPM; _____ TDH; _____ RPM; _____ % Eff.; CDS No. _____

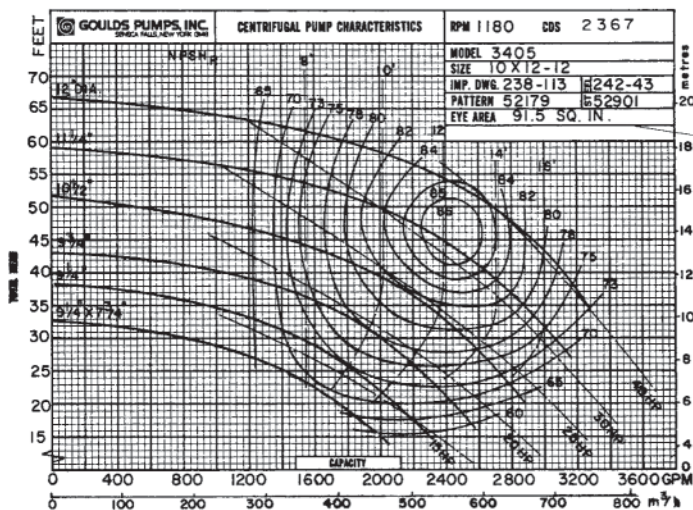
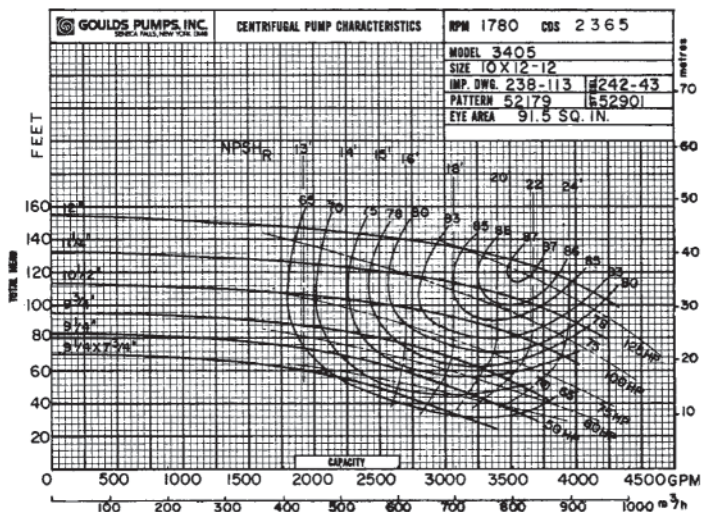


FIGURE 7.58 Centrifugal pump performance at the selected speeds 1780 and 1180 rpm. (Courtesy Gould's Pumps Inc., Seneca Falls, NY.)

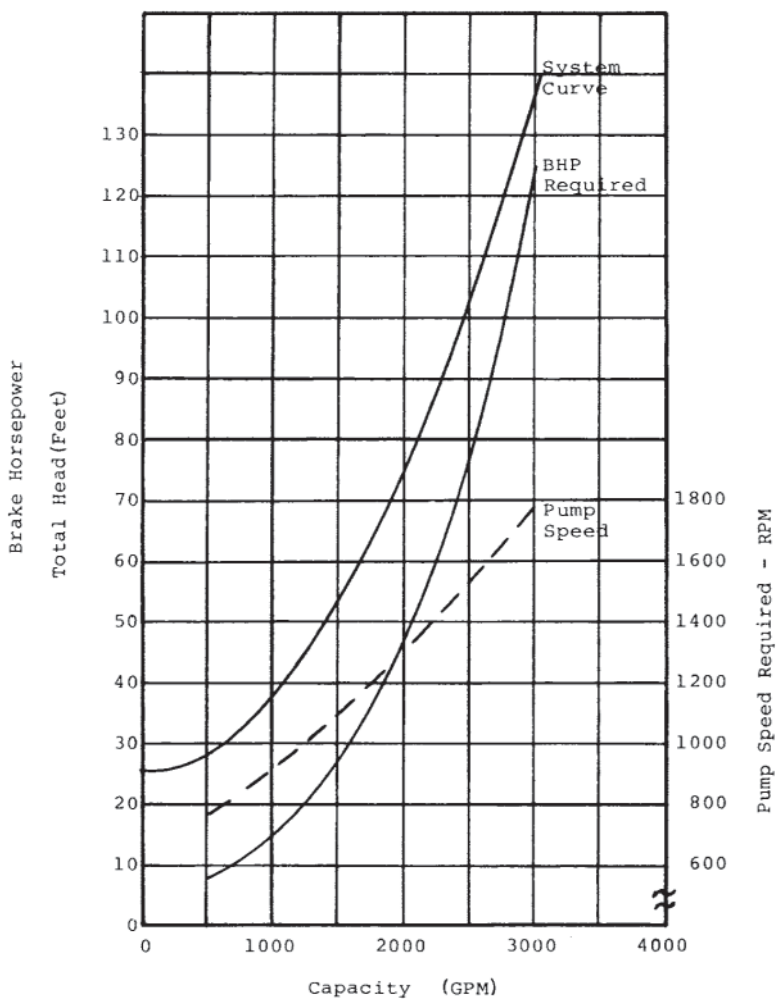


FIGURE 7.59 Sample fluid system characteristic.

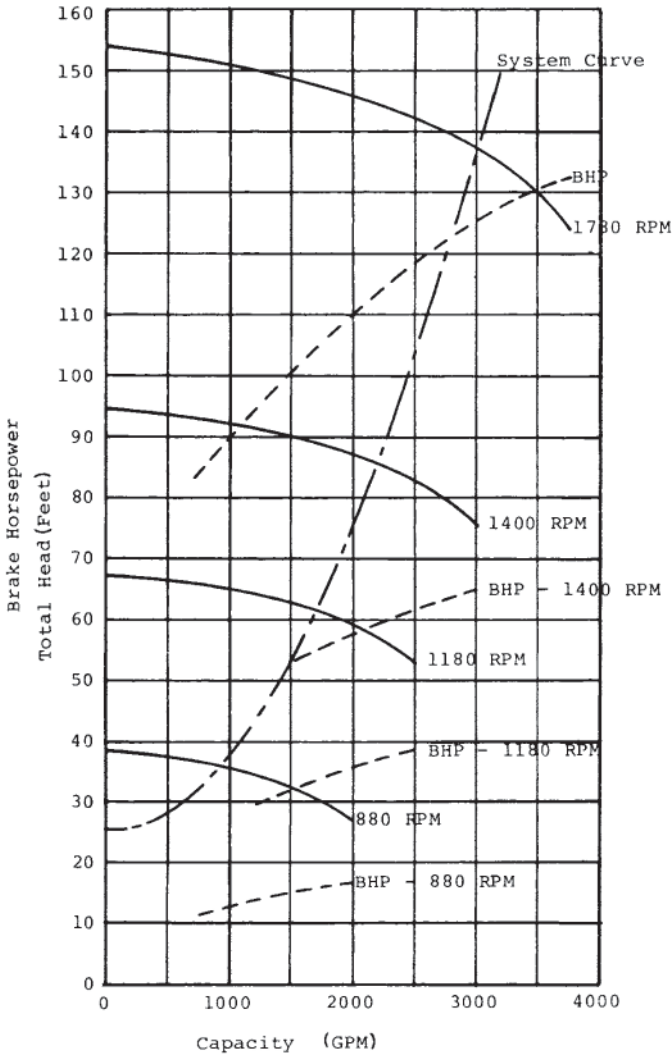


FIGURE 7.60 Centrifugal pump characteristics.

TABLE 7.4 Summary of Sample Calculations for Adjustable-Flow Systems

Flow rate, %	Flow, gpm	Pump ^a BHP required	Throttling system		Eddy current drive or fluid drive		AC variable-frequency system		Wound-rotor motor with slip loss recovery	
			Input, kW	Losses, kW	Input, kW	Losses, kW	Input, kW	Losses, kW	Input, kW	Losses, kW
100	3000	125	100.81	7.56	107.26	14.0	103.96	10.71	101.91	8.66
75	2250	60	92.65	47.89	61.29	16.5	51.15	6.39	51.45	6.69
50	1500	28	80.56	59.67	36.89	16.0	24.60	3.72	25.17	4.28

^a For adjustable-speed pump.

Figure 7.59 shows the system flow characteristic and the centrifugal pump characteristics at various pump speeds for the specific application. Figure 7.60 shows the pump characteristic at various speeds and the system characteristics as a function of flow requirements.

The pump BHP, the power input, and the power losses from the power line to the pump can be calculated for each method of flow control. A summary of these calculations is shown in Table 7.4 for three flow conditions: full flow (100%), 75% flow, and 50% flow.

The annual power savings and present net worth of the savings for each system can be determined for a specific set of conditions. To continue the sample calculations, set the following conditions:

Annual operating hours, 8000 hr

Operating cycle:

full flow, 50% of the time

75% flow, 30% of the time

50% flow, 20% of the time

Full-flow BHP, 125 hp

Initial power rate, \$0.06/kWh

Annual increase in power rates, 15%

Cost of money, 20%

Tax rate, 40%

TABLE 7.5 Annual Energy Savings and Net Present Worth for Adjustable-Speed Pumping Systems^a

System	Annual savings, kWh	Net present worth, \$
Fluid drive or eddy current system	120,056	30,907
AC variable-frequency system	179,536	45,448
Wound rotor with slip recovery system	183,104	47,141

^a Base for comparison: throttling system.

The summary of these calculations in [Table 7.5](#) shows the savings that can be achieved by means of adjustable-speed pumping systems compared to a throttling-type system. These calculations indicate that substantial power savings can be achieved with variable-speed types of pumping systems. The selection of the most effective system depends on the comparison of the system cost to the net present worth of the system savings and on application factors such as environment and maintenance.

7.5 APPLICATIONS TO CONSTANT-TORQUE LOADS

A wide variety of loads can be considered constant-torque loads. Conveyers are probably the most common type of constant-torque application. The means of achieving adjustable speed for these types of loads has been basically mechanical methods or DC drives. The adjustable-frequency induction motor drive systems add a new dimension to the method of adjusting the output speed for such loads.

A comparison of the annual power costs for the following adjustable-speed drive systems driving a constant-torque load is made in the following example:

- Eddy current or hydrodynamic drives
- Mechanical adjustable-speed drives
- Adjustable-frequency induction motor drives

EXAMPLE

Consider a conveyer operated over approximately a 3:1 speed range with a constant-torque requirement of 30 lb-ft.

Annual operating hours: 2000
Duty cycle:

- 1750 rpm, 1200 hr
- 1200 rpm, 500 hr
- 600 rpm, 300 hr

Power rates: \$0.06/kWh

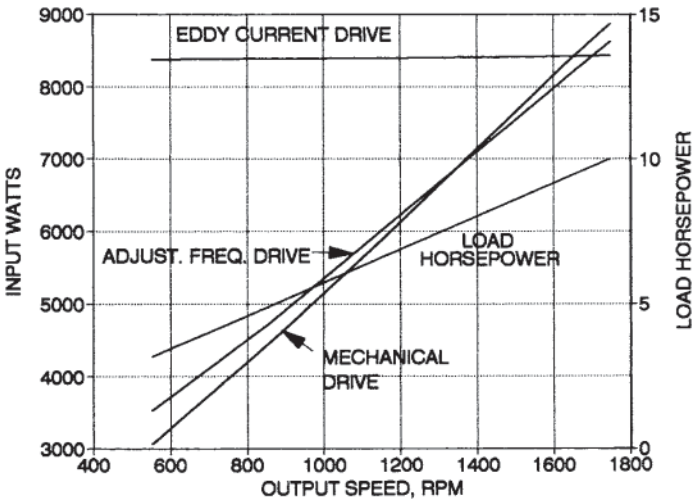


FIGURE 7.61 Input watts for a constant-torque load with various adjustable-speed drive systems.

TABLE 7.6 Annual Power Costs for Example Constant-Torque Conveyor Drive Systems

System	Annual energy consumption, kWh	Annual power cost, \$
Eddy current drive	16,817	1,008.99
Mechanical adjustable-speed drive	14,649	878.94
Adjustable-frequency drive	14,544	872.64

Figure 7.61 shows the input power and load horsepower for each of the above drive systems over the speed range considered. The input power is based on a 10-hp, 1800-rpm energy-efficient drive motor for each system and the efficiency of each system.

Based on these data, the annual power consumption in kilowatt-hours and the power cost in dollars for each of the above systems are shown in Table 7.6. With the narrow range in annual power cost, additional factors such as initial cost, ease in operation, remote control features, environment, and maintenance must be considered in selecting the proper adjustable-speed drive system for a constant-torque load.